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Substance Flow Analysis in Finland – Four Case Studies on N and P Flows

Yhteenveto: Ainevirta-analyysi Suomessa – neljä esimerkkitapausta typen ja fosforin virroista

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Contents

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II **Antikainen, R**., Lemola, R., Nousiainen, J.I., Sokka, L., Esala, M., Huhtanen, P., & Rekolainen, S. 2005. Stocks and flows of nitrogen and phosphorus in the Finnish food production and consumption system. *Agriculture, Ecosystems and Environment* 107: 287–305.

III Saikku, L., **Antikainen, R.,** & Kauppi, P.E. 2007. Nitrogen and phosphorus in the Finnish energy system,1900–2003. *Journal of Industrial Ecology* 11 (1): 103–119 .

IV Sokka, L., **Antikainen, R.,** & Kauppi, P. 2004. Flows of nitrogen and phosphorus in municipal waste – a substance flow analysis in Finland. *Progress in Industrial Ecology* 1(1–3): 165–186.

Riina Antikainen is the principal author in charge of data collection and analysis for *Papers I and II*. In *Paper I*, Reija Haapanen helped to collect and analyse data. She also participated in the preparation of the manuscript. Seppo Rekolainen commented on the manuscript. In the *Paper II*, Riitta Lemola, Jouni Nousiainen and Laura Sokka helped to collect data. All co-writers of *Papers I and II* played an essential role as commentators on the study and on the manuscript.

In *Paper III,* SFA data were jointly collected and analysed by Laura Saikku and Riina Antikainen. The ImPACT analysis was performed by Laura Saikku. The manuscript was co-written by Laura Saikku and Riina Antikainen. Pekka Kauppi commented on the manuscript.

In the *Paper IV,* data were jointly collected and analysed and the manuscript co-written by Laura Sokka and Riina Antikainen. Pekka Kauppi commented on the manuscript.

Abstract

Nitrogen (N) and phosphorus (P) are essential elements for all living organisms. However, in excess, they contribute to such environmental problems as aquatic and terrestrial eutrophication (N, P), acidification (N), global warming (N), groundwater pollution (N), depletion of stratospheric ozone (N), formulation of tropospheric ozone (N) and poor urban air quality (N). Globally, human action has multiplied the volume of N and P cycling since the onset of industrialization. The multiplication is a result of intensified agriculture, increased energy consumption and population growth.

Industrial ecology (IE) is a discipline, in which human interaction with the ecosystems is investigated using a systems analytical approach. The main idea behind IE is that industrial systems resemble ecosystems, and, like them, industrial systems can then be described using material, energy and information flows and stocks. Industrial systems are dependent on the resources provided by the biosphere, and these two cannot be separated from each other. When studying substance flows, the aims of the research from the viewpoint of IE can be, for instance, to elucidate the ways how the cycles of a certain substance could be more closed and how the flows of a certain substance could be decreased per unit of production (= dematerialization). IE uses analytical research tools such as material and substance flow analysis (MFA, SFA), energy flow analysis (EFA), life cycle assessment (LCA) and material input per service unit (MIPS).

In Finland, N and P are studied widely in different ecosystems and environmental emissions. A holistic picture comparing different societal systems is, however, lacking. In this thesis, flows of N and P were examined in Finland using SFA in the following four subsystems: I) forest industry and use of wood fuels, II) food production and consumption, III) energy, and IV) municipal waste. A detailed analysis at the end of the 1990s was performed. Furthermore, historical development of the N and P flows was investigated in the energy system (III) and the municipal waste system (IV). The main research sources were official statistics, literature, monitoring data, and expert knowledge.

The aim was to identify and quantify the main flows of N and P in Finland in the four subsystems studied. Furthermore, the aim was to elucidate whether the nutrient systems are cyclic or linear, and to identify how these systems could be more efficient in the use and cycling of N and P. A final aim was to discuss how this type of an analysis can be used to support decision-making on environmental problems and solutions.

Of the four subsystems, the food production and consumption system and the energy system created the largest N flows in Finland. For the creation of P flows, the food production and consumption system (Paper II) was clearly the largest, followed by the forest industry and use of wood fuels and the energy system. The contribution of Finland to N and P flows on a global scale is low, but when compared on a per capita basis, we are one of the largest producers of these flows, with relatively high energy and meat consumption being the main reasons.

Analysis revealed the openness of all four systems. The openness is due to the high degree of internationality of the Finnish markets, the large-scale use of synthetic fertilizers and energy resources and the low recycling rate of many waste fractions. Reduction in the use of fuels and synthetic fertilizers, reorganization of the structure of energy production, reduced human intake of nutrients and technological development are crucial in diminishing the N and P flows. To enhance nutrient recycling and replace inorganic fertilizers, recycling of such wastes as wood ash and sludge could be promoted.

SFA is not usually sufficiently detailed to allow specific recommendations for decision-making to be made, but it does yield useful information about the relative magnitude of the flows and may reveal unexpected losses. SFA studies should be supported with other methods such as LCA. Data uncertainties are high in this type of analysis. Use of quantitative uncertainty analysis is therefore recommended. Definition of the system boundaries significantly affects conclusions drawn from SFA results.

Sustainable development is a widely accepted target for all human action. SFA is one method that can help to analyse how effective different efforts are in leading to a more sustainable society. SFA's strength is that it allows a holistic picture of different natural and societal systems to be drawn. Furthermore, when the environmental impact of a certain flow is known, the method can be used to prioritize environmental policy efforts.

Yhteenveto

Typpi (N) ja fosfori (P) ovat elintärkeitä alkuaineita kaikille olioille. Liiallisissa määrin ympäristössä ne kuitenkin aiheuttavat monia ongelmia kuten vesistöjen ja maaperän rehevöitymistä. Typpi ja sen eri yhdisteet edesauttavat happamoitumista, ilmastonmuutosta, pohjaveden pilaantumista, stratosfäärin otsonin vähenemistä, troposfäärin otsonin muodostumista ja ilmanlaadun heikkenemistä. On arvioitu, että maailmanlaajuisessa mittakaavassa ihmistoiminta on moninkertaistanut typen ja fosforin kiertomäärän ja -nopeuden teollistumisesta alkaen. Pääasiallisina syinä ovat maatalouden tehostuminen, energiankäytön lisääntyminen ja väestömäärän kasvu.

Teollisessa ekologiassa ihmisten vuorovaikutusta ekosysteemien kanssa tarkastellaan systeemianalyyttisen lähestymistavan avulla. Teollisen ekologian perusajatus on, että teolliset järjestelmät muistuttavat ekosysteemeitä, ja niitä voidaan näin ollen kuvata materiaali-, energia- ja tietovirtojen ja –varantojen avulla. Teolliset järjestelmät ovat riippuvaisia biosfäärin tarjoamista resursseista, eikä näitä kahta voida erottaa toistaan. Kun tutkitaan ainevirtoja, on teollisen ekologian näkökulmasta tavoitteena muun muassa etsiä ja havainnollistaa tapoja, kuinka tietyn aineen kierto voisi olla entistä suljetumpi. Lisäksi voidaan tutkia esimerkiksi dematerialisaatiota eli sitä, miten tietyn yhdisteen virtoja voitaisiin pienentää tuotettuun määrään verrattuna. Teollisen ekologian menetelmiä ovat analyyttiset tutkimusmenetelmät kuten materiaali- ja ainevirta-analyysit (MFA, SFA), energiavirta-analyysi (EFA), elinkaariarviointi (LCA) ja materiaalipanos per palvelusuorite (MIPS).

Suomessa typpeä ja fosforia sekä niiden käyttäytymistä, kiertoa ja vaikutuksia on tutkittu kattavasti eri ekosysteemeissä. Lisäksi päästöjä ympäristöön on selvitetty paljon. Kattava kokonaiskuva, joka vertailee typpeä ja fosforia eri yhteiskunnallisissa järjestelmissä, on kuitenkin puuttunut. Tässä tutkimuksessa typen ja fosforin virtoja tarkasteltiin ainevirta-analyysilla neljässä järjestelmässä: I) metsäteollisuus ja puupolttoaineiden käyttö, II) ruoan tuotanto ja kulutus, III) energia ja IV) yhdyskuntajätteet. Näistä tehtiin yksityiskohtainen 1990-luvun loppua koskeva analyysi. Lisäksi typen ja fosforin virtojen historiallista kehitystä tutkittiin energiajärjestelmässä (III) ja yhdyskuntajätejärjestelmässä (IV). Pääasialliset tietolähteet olivat viralliset tilastot, kirjallisuus, päästöjen tarkkailuaineisto ja asiantuntija-arviot.

Tutkimuksen tarkoituksena oli tunnistaa tärkeimmät typen ja fosforin virrat neljässä järjestelmässä Suomessa sekä laskea virtojen suuruus. Lisäksi tarkoituksena oli tarkastella, ovatko kyseisten järjestelmien typpi- ja fosforivirrat suljettuja vai avoimia sekä löytää tapoja, kuinka typen ja fosforin käyttöä ja kiertoa voitaisiin tehostaa. Tavoitteena oli myös pohtia, kuinka hyvin ainevirta-analyysi soveltuu ympäristöongelmia ja niiden ratkaisuja koskevan päätöksenteon tueksi.

Tarkastelluista neljästä järjestelmästä ruoan tuotanto ja kulutus ja energiajärjestelmä tuottivat suurimmat typen virrat. Fosforin virtojen aiheuttajana ruoan tuotanto ja kulutus oli merkittävin. Suomen merkitys maailmanlaajuiseen ravinnekiertoon on vähäinen, mutta asukasmäärään suhteutettuna Suomi on yksi merkittävämpiä typpi- ja fosforivirtojen aiheuttajia. Syitä ovat suhteellisen korkea energian- ja lihankulutus.

Tutkimus osoitti kaikkien neljän systeemin avoimuuden, mikä johtuu suomalaisen kaupan kansainvälisyydestä, keinolannoitteiden mittavasta käytöstä, suhteellisen suuresta energiankulutuksesta ja monien jätejakeiden alhaisesta kierrätysasteesta. Polttoaineiden ja keinolannoitteiden käytön vähentäminen, energiantuotantorakenteen uudistaminen, ihmisten ravinteiden kulutuksen (ruoassa) vähentäminen ja teknologinen kehitys ovat olennaisia keinoja pienentää typpi- ja fosforivirtoja. Puutuhkan ja lietteen kierrätyksen avulla voitaisiin edistää ravinnekiertojen sulkeutumista ja korvata keinolannoitteita.

Ainevirta-analyysi ei ole yleensä riittävän tarkka menetelmä tuottaakseen yksityiskohtaisia johtopäätöksiä päätöksentekijöille. Sen avulla voidaan tuottaa käyttökelpoista tietoa eri virtojen suhteellisista osuuksista ja se voi myös paljastaa odottamattomia aineiden hävikkejä. Ainevirta-analyysia voidaan ja on usein tarpeellista tukea muilla menetelmillä kuten elinkaariarvioinnilla. Koska lähtötietojen epävarmuus on usein suuri tämän tyyppisissä analyyseissä, on epävarmuus- ja herkkyystarkastelujen käyttö suositeltavaa. Tarkasteltavan järjestelmän rajojen määrittäminen on olennainen tekijä johtopäätelmien kannalta.

Kestävyys on yleisesti hyväksytty tavoite kaikessa ihmistoiminnassa. Ainevirta-analyysi on yksi menetelmä, jonka avulla voidaan tarkastella kohti kestävämpää yhteiskuntaa johtavia tapoja. Ainevirta-analyysin vahvuutena on, että sen avulla voidaan tuottaa kokonaiskuva eri luonnon- ja yhteiskunnan järjestelmistä. Kun lisäksi kunkin virran ympäristövaikutus tiedetään, menetelmää voidaan käyttää ympäristöpoliittisten toimenpiteiden priorisointiin.

List of abbreviations

ADP	Adenosine diphosphate
ATP	Adenosine triphosphate
DAIQUIRI	Deposition, air quality and integrated regional information, regional deposition model
DNA	Deoxyribonucleic acid
EFA	Energy flow analysis
EU	European Union
Fe	Iron
FFRI	Finnish Forest Research Institute
FFI (F)	Finnish Forest Industries (Federation)
GDP	Gross domestic product
IE	Industrial ecology
ISO	International Organization for Standardization
LCA	Life cycle assessment
METINFO	Statistical information system of the Finnish Forest Research Institute, see http://www.metla.fi/metinfo/index-en.htm
MFA	Material flow analysis
MIPS	Material input per service unit
N	Nitrogen
NH_3	Ammonia
NO, NO_x	Nitrogen oxide(s)
NO_3^-	Nitrate
N_2O	Nitrous oxide
P	Phosphorus
PAHs	Polycyclic aromatic hydrocarbons
P_2O_5	Phosphorus oxide
PVC	Polyvinyl chloride
RNA	Ribonucleic acid
SFA	Substance flow analysis
SLICES	Separated land use/land cover information system
SYKE	Finnish Environment Institute
TMR	Total material requirement
VAHTI	Environmental emission database maintained by Finnish environmental administration

1. Introduction

1.1. Background

A recent extensive global environmental assessment identified that one of the main global ecosystem problems is the increase in the likelihood of non-linear changes that have detrimental effects on human well-being (Millennium Ecosystem Assessment 2005). Examples include the consequences of eutrophication, such as deterioration of water quality and creation of ’dead zones’ in coastal waters.

Eutrophication is caused by excess supply of nutrients in an aquatic or terrestric system. In natural ecosystems, nutrients have balanced cycles. Human interference with the flows has disturbed the cycles, causing accumulation of nutrients to the soil and waters, and thereby, problems caused by the nutrients. Globally, human alteration of the ecosystems has been more rapid and extensive over the past 50 years than ever before, the main reasons for the change being the growing demand for food, fresh water, timber, fibre and fuel (Millennium Ecosystem Assessment 2005). Moreover, since 1960, flows of reactive (biologically available) nitrogen (N) in terrestrial ecosystems have doubled and flows of phosphorus (P) have tripled.

Large-scale human interference with the N and P cycles started with industrialization. Agricultural production and energy consumption began to escalate. At the beginning of the 1900s, inorganic fertilizers were invented, and they gradually freed plant production from animal production. Earlier, manure was the main supplier of nutrients to the agricultural soil. N to fertilizers is obtained from the atmospheric N pool via Haber-Bosch synthesis. The main source of fertilizer P is apatite, mined from bedrock. Inorganic fertilizers along with improved agricultural technological knowledge have increased plant yields. Simultaneously, however, manure has become a problem, being dumped into fields. No one appeared to be concerned about the nutrient balances.

In energy production, nutrients are freed from their short- and long-term storages (biomass, fossil fuels). In the combustion process, N is freed to the atmosphere, and is partially deposited on soils and waters, causing eutrophication, acidification and air quality problems. P stays in ash during combustion, and its fate depends on the placement of the ash.

In Finland also, industrialization, and the growing population, and therefore the increasing need for raw materials, have intensified the use of mineral resources, wood and agricultural soil. The development has had its drawbacks. Finland is mainly located on the catchment area of the Baltic sea, which is one of the world’s most polluted sea regions. Eutrophication is a major concern. Harmful algal blooms are an annual phenomenon, and there are large anoxic bottom areas in the sea (see e.g. Helcom 2001, Kiirikki et al. 2001, Pitkänen et al. 2001). The Finnish lakes are also sensitive to eutrophication because they are shallow and the water turnover rate is often slow. Algal blooms are an annual nuisance in several Finnish lakes (Lepistö 1999, Rissanen and Lepistö 2002). The long winter season worsens the situation. For example, oxygen depletion easily occurs in a shallow eutrophicated lake if the ice cover is formed before the water has mixed. According to the recently accepted new water protection guidelines, eutrophication of the Baltic Sea and the inland waters is the most severe environmental problem of Finnish waters, and the nutrient load to waters needs to be reduced in all sectors (Finnish Council of State 2006).

Acidification is another environmental problem related to N. Acidification means reduced buffer capacity of soil and water against acid deposition, which is due to nitrogen oxide, ammonia and sulphur oxide emissions. In recent years, acid deposition in Finland has decreased significantly due to tightened emission limits and technological development. Most of the reduction has taken place in the sulphur deposition. Deposition of nitrogen oxides and ammonia, by contrast, has not declined substantially. This has increased the relative importance of N as well as imported deposition in general in acidification (Syri 2001). Furthermore, N contributes to depletion of the stratospheric ozone, global climate changes and formulation of a tropospheric ozone.

1.2. Industrial ecology and industrial metabolism

Industrial ecology (IE) is a systems analytical approach for studying the interactions between human actions and the environment. The term IE has been used in the literature periodically since the 1970s (Erkman 1997). At the foundation of the current IE concept is the article by Frosch and Gallopoulos (1989). The basic idea of IE is that industrial systems resemble ecosystems, and, like them, industrial systems can then be described using material, energy and information flows and stocks. Industrial systems are dependent on the resources provided by the biosphere, and these two cannot be separated from each other. The aim of IE is to understand how the industrial system works, how it is regulated and how it interacts with the biosphere. Then, on the basis of what we know about the ecosystems, to determine how the industrial system could be restructured to make it more compatible with the functioning of natural ecosystems (Erkman 1997). Furthermore, IE systematically analyses the potentials to optimize the total industrial material cycle from virgin material to finished product to waste product and to ultimate disposal (Graedel 1994).

Even though IE currently is recognized as a research field of its own, its definition and contents are not fully established. The same questions of sustainable use of natural resources have been and are examined in other fields, such as ecological economics and environmental management, which some include in IE and others as independent research fields. Moreover, as the basis of IE lies in analysing the physical material flows, many of its research questions are also familiar to traditional natural and engineering sciences. Currently, the definition and content of IE is extensive encompassing several related fields of environmental sciences, and, in fact, IE is more of an umbrella concept than a precisely defined theory. The fields under IE mainly handle technological and natural aspects of sustainability. Social sciences, shedding light on e.g. consumer behaviour, can yield essential knowledge and widen the IE approach. However, it is questionable whether a need exists for merging; if knowledge is utilized from allied fields, then the boundaries and identity of IE will not need to be expanded too diffusely (Lifset and Graedel 2002).

Industrial metabolism (introduced by Ayres in the late 1980s, see Ayres 1989) is another concept closely related to IE and often classified as a subcategory of IE. Industrial metabolism is aimed at understanding the circulation of materials and energy flows linked to human activity. Its viewpoint is narrower than that of IE (Erkman 1997). The scholarly basis of industrial metabolism lies back some 150 years in natural and social sciences (Fischer-Kowalski 2002). According to Ayres himself, “the metabolism of industry is the whole integrated collection of physical processes that convert raw materials and energy, plus labour, into finished products in a (more or less) steady state condition”, the economic system being the metabolic regulatory system (Ayres 1994). Industrial metabolism can be studied at a number of spatial and functional levels, from global to local and from worldwide economy to e.g. an enterprise’s single unit process.

To study industrial systems and their impact on the environment , analytical tools such as life cycle assessment (LCA), material flow analysis (MFA), substance flow analysis (SFA), energy flow analysis (EFA), physical input-output accounting and material input per service unit (MIPS) calculations are used. These tools are based on the systems perspective, and their purpose is to support decision-making processes. For more information about LCA, MFA and physical input-output accounting, see e.g. Ayres and Ayres (2002) and ISO (2006a, 2006b); for MIPS, see Schmidt-Bleek (1994, 2000). SFA, the tool used in this study, is described in more detail in Section 3.1.

Identifying potential ways of closing material cycles and diminishing material flows is an important goal in studying substance and material flows. These two objectives are described in more detail below.

1.2.1. Closing material cycles

In IE, strong emphasis is given to finding the ways to close material cycles. By efficient cycling of resources, the consumption of virgin raw materials can be reduced. Graedel (1994) has created a model of three types of ecology to illustrate material and energy flows in ecosystems (Fig. 1). Type I ecology is the most linear and dependent on the external material and energy resources creating an unlimited amount of waste. The quasi-cyclic material flows of Type II ecology are more efficient than those in the Type I system. Type II ecology is still unsustainable in the long run, as it needs resources outside the system and it produces waste. In Type III ecology, a complete cyclicity has been achieved, and resources and waste need not be defined, as waste to one system component is a resource of another. Type III ecology can be seen as the target for industrial system design; however, the spatial and temporal system boundaries set greatly define the analysis of the system (see also discussion, Sections 5.2 and 5.4). The results of the analysis are also likely to change according to the system boundaries. For example, when considering N, one system boundary definition relates to the atmospheric pool of N_2, and the N cycle can, in this context, be defined at two levels: 1) cyclic N flow includes the atmospheric N_2 cycle, and N_2 released to atmosphere is not a loss but a resource for natural or artificial denitrification processes; or 2) cyclic N flow does not include the atmospheric N_2 cycle; cyclicity refers to N flows in materials, and N_2 lost to atmosphere is considered as waste lost from the system because its recapture requires energy and resources.

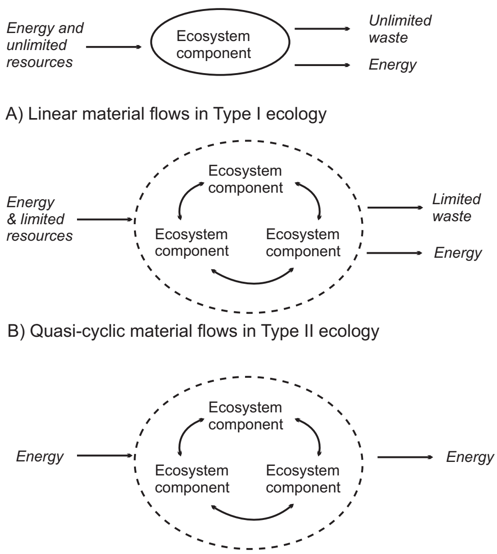


Fig. 1. Three types of ecology (based on Graedel 1994).

In this context, waste can be defined broadly to mean in addition to solid waste, all outputs to air, water and soil. Using this definition, a target system of the type III ecology would not cause any emissions to air, water or soil (zero-emission system). Furthermore, it would only utilize the resources once taken into use. In reality, this type of optimal system is almost impossible to achieve and should be regarded more as a metaphoric model to enhance understanding of the emission and waste reduction, recycling and reuse.

1.2.2. Diminishing of material flows

Decline in material use of a society is one of the key issues when discussing the promotion of sustainable development. The issue itself is rather simple and includes three components: material production and/or consumption, environmental pressure and economic production (see e.g. Tapio et al. 2007). However, there is no consensus on the terminology and definitions related to reduction in material flows. Frequently used terms include dematerialization, immaterialization, delinking and decoupling. Van der Voet et al. (2003) connect dematerialization to material inputs and distinguish between absolute (strong) and relative (weak) dematerialization. Absolute dematerialization refers to a reduction in the total amount of material input of a society. Relative dematerialization refers to a decline in material input per capita or per GDP. Tapio et al. (2007), by contrast, describe dematerialization as linking environmental harm and material production and/or consumption (e.g. a reduction in carbon intensity of energy production and carbon intensity of transport). In their definition, immaterialization denoted the decoupling of both material production and consumption from economic production (e.g. reduction of energy intensity and transport intensity), whereas Jokinen et al. (1998) see immaterialization as decoupling of material consumption from economic production, and dematerialization as decoupling of material production from economic production. Decoupling and delinking refer to a reduction in environmental degradation in relation to economic growth. Here, a broad definition for dematerialization is used; the term refers to the decline in material use per service output and can be studied by taking into account all materials used by a society (total material requirement, TMR) or by concentrating on a specific material or substance.

Dematerialization is closely linked to the discussion on earth's limited resources. For N, there are obviously no problems in sufficiency, as vast N storages exist in the atmosphere. However, atmospheric N is mostly in an unusable form, and large amount of energy are needed to convert it to a form that can be exploited for fertilization and by other industries. P, by contrast, is a limited resource, and an estimate has been presented that the current economically exploitable reserves will be depleted within 60-130 years (Steen 1998).

Dematerialization can take place in many ways, for example, by increasing efficiency, by substitution, by re-use or recycling or by sharing (van der Voet et al. 2003). Increased efficiency will occur when less raw materials are used to produce the same product (e.g. yoghurt packages are now more compact than before). Dematerialization by substitution (i.e. transmaterialisation) will happen when heavier raw materials are replaced by lighter ones. Car sharing or sharing of libraries has the same effect. By re-using and recycling materials, the need for raw materials diminishes, and thus, the material input to society decreases. When considering re-use and recycling, the concept of dematerialization and the concept of closing material cycles (see above) are, in practice, the same: only the terminology differs.

Dematerialization is not a problem-free concept. It has been criticized, among other things, for not taking into account the chemical form of materials. If, for instance, heavy materials are substituted with lighter but more toxic ones, the actual environmental impact may increase. Dematerialization can also lead to growing energy consumption if the production of substituted materials is more energy-intensive or if the infrastructure for re-use, recycling or sharing requires more transportation.

1.3. Topics under investigation

N and P are two elements essential to all living organisms. N is used to produce numerous complex organic molecules such as amino acids, proteins and nucleic acids. Animals need P for their bones and teeth, and all living organisms require P in cell metabolism. P also plays a major role in biological molecules such as DNA and RNA, where it forms part of the structural framework of these molecules. In addition, P is a component in ATP (adenosine triphosphate) and ADP (adenosine diphosphate), which control cell energy metabolism. P is also needed as a component in several other compounds and to control the cell acid-base equilibrium.

1.3.1. Nitrogen (N)

N is an abundant element, with 78% of the atmosphere comprising elemental N (as N_2). Despite this, vegetation is not, in general, able to utilize elemental N_2, but only soluble N or ammonium compounds. This means that fixation of N and conversion of N to a bioavailable form, are essential for life. Before synthetic fertilizer production was invented, the only means of increasing bioavailable N in the biosphere was N-fixing organisms such as *Rhizobium* bacteria and cyanobacteria. Another, much smaller pathway for N fixation was lightning, causing formulation of nitric oxide (NO), which further oxidizes to nitrate (NO_3^-) and is deposited to earth in dry or wet form.

In soil, N exists mainly in organic form. To be available for plants, organic N is transformed by microbial processes to NH_4^+ (ammonification) or further to NO_3^- (nitrification) (Fig. 2). Nitrification is a two-step process. Ammonia is first oxidized to NO_2^- which in turn is further oxidized to NO_3^-. Many species of soil bacteria are capable of reducing nitrates and nitrites to gaseous form (NO, N_2O, N_2) in a process called denitrification, which releases N back to the atmosphere. N can also be released from the soil surface as ammonia (NH_3). Denitrification is promoted by high soil moisture conditions, neutral soil pH, high soil temperatures, a low rate of oxygen diffusion as well as the presence of soluble organic matter and nitrate (Mengel and Kirkby 1982).

In waters, N is found in molecular form (N_2), ammonia (NH_4^+), nitrates (NO_2^-), nitrites (NO_3^-), dissolved organic nitrogen or particulate organic nitrogen. The cycling of N in waters is basically the same as in soil including processes of ammonifiction, nitrification and denitrification.

Human action has added new dimensions to the natural N cycle (Fig. 3). At present, N cycling in the global food production system is largely based on the Haber-Bosch synthesis, in which atmospheric molecular N and hydrogen are combined to NH_3 at high temperatures and pressures in the presence of catalysing agents. The world's first commercial

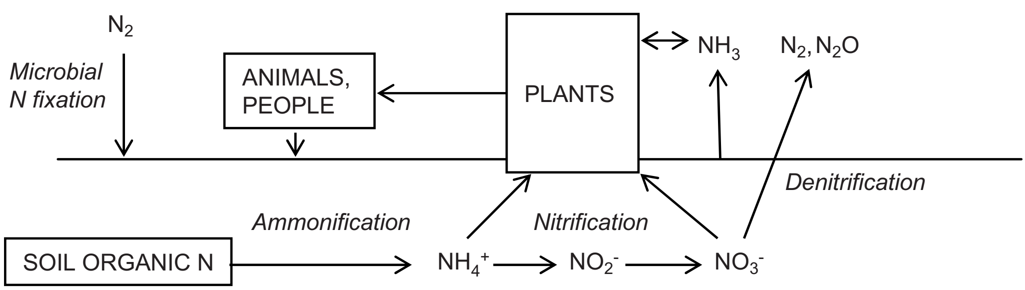


Fig. 2. N cycle in nature (based on Mengel and Kirkby 1982).

ammonia factory was established in Germany in 1913. The production of ammonia remained relatively low until the end of World War II, after which the production gradually grew. In the 1960s, technological innovations cut the electricity consumption of the fertilization production process by more than 90%, reducing the production costs of ammonia and subsequently increasing the production enormously. The most important ammonia application is fertilizers, which in the United States, accounts for ca. 70% of ammonia consumption (including exports and losses) (Febre Domene and Ayres 2001). Other important applications are plastics and fibres (about 5% of US N consumption) and explosives (ca. 3% of US N consumption).

Significant transforming processes of atmospheric N to nitrogen oxides (NO_x) and nitrous oxide (N_2O) include the combustion processes. Furthermore, some industrial processes, such as the manufacturing of fertilizers, release N_2O and NH_3 to the atmosphere, while agriculture, especially farm animal manure, is the main source of NH_3 emissions. Fluxes from the atmosphere to the land and water surface include deposition of NO_x and NH_3.

Several studies have identified a significant intensification in global N flows after the start of industrialization (Ayres et al. 1994, Vitousek et al. 1997, Millennium Ecosystem Assessment 2005). The main reasons for this are the production of N fertilizers, increased planting of leguminous crops, combustion of fossil fuels, increases in the world cattle population and changes in land use (Ayres et al. 1994, Vitousek et al. 1997). During the mid-1990s, inorganic fertilizers accounted for approximately 46% of the world's annual N inputs on croplands (Table 1).

Table 1: Annual balances of nitrogen flows in the world's croplands during the mid-1990s (Smil 1999).

Flows	Mt N a^{-1} mean	(min-max)	% mean
Inputs	*169*	*(151–186)*	*100*
Seeds	2		1
Atmospheric deposition	20	(18–22)	12
Irrigation water	4	(3–5)	2
Crop residues	14	(12–16)	8
Animal manure	18	(16–20)	11
Biofixation	33	(25–41)	20
Inorganic fertilizers	78	(75–80)	46
Outputs	165	(143–190)	*100*
Harvested plants	85		52
Losses			
NO emissions	4	(1–6)	2
N_2O emissions	4	(1–7)	2
N_2 emissions	14	(11–18)	8
NH_3 volatilization	11	(8–14)	7
NO_3^- leaching	17	(14–20)	10
Soil erosion	20	(18–25)	12
Losses from tops of plants	10	(5–15)	6
Balance	*+4*	*((+8)–(–4))*	

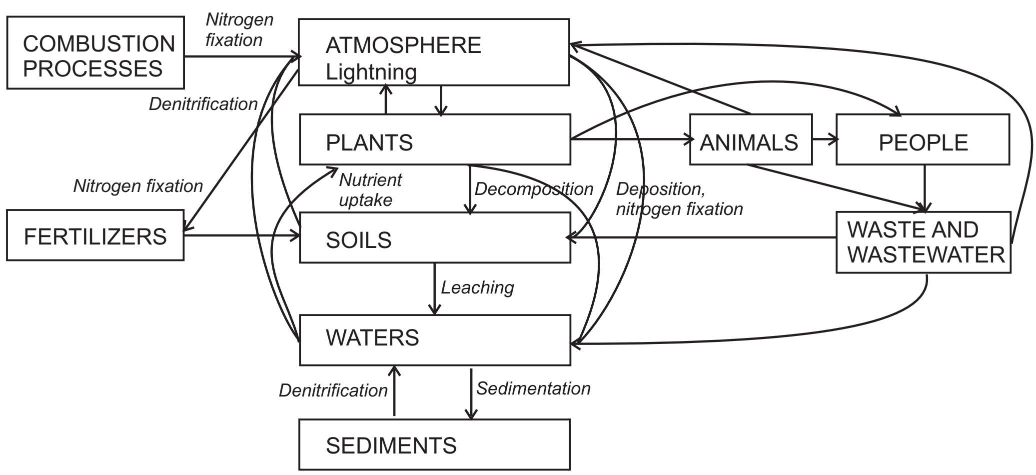


Fig. 3. Simplified global cycle of N (based on Mengel and Kirkby 1982 and Smil 1997).

As the flows of N have increased so have direct and indirect harmful effects on both human health and the environment. These include such problems as eutrophication and acidification effects on the water and soil ecosystems and depletion of stratospheric ozone by N_2O emissions. Furthermore, the emissions of N_2O induce global climate change and formulation of tropospheric ozone. The beneficial and detrimental effects of reactive N have been summarized by Cowling et al. (2001) (Table 2).

The primary production in the Baltic Sea (excluding Bothnian Bay) is mainly limited by the concentration of available N (Granéli et al. 1990, Kivi 1993, Hänninen et al. 2000). N is also the primary production limiting nutrient in many Finnish coastal fresh waters (Pietiläinen and Räike 1999). In Finland, agriculture is estimated to cause approximately 50% of the N load to waters (Fig. 4). Atmospheric deposition and municipalities are other main N sources.

The Finnish environment, especially nutrient-poor lakes and forests in the Northern Finland, is relatively sensitive to acidification due to low buffering capacity. Attention was paid to increasing N emissions in the 1980s, but, in Europe, the emissions continued to grow until the 1990s, after which they have declined. In total, NO_x emissions in Europe were estimated to have decreased by 24% and NH_3 emissions by 20% from 1980 to 2000 (Lövblad et al. 2004a, 2004b). In Finland, the corresponding reductions are 21% (NO_x) and 10% (NH_3). The main sources of NO_x emissions to air in Finland are transportation and energy production (Statistics Finland 2004). Agriculture is the predominant source of NH_3 emissions (Finnish Environment Institute 2007).

The nitrogen deposition trends in Finland are in agreement with declining European and Russian N emissions. N emissions increased until the late 1980s and then slightly declined during the 1990s. By then, mean annual NO_3-N and NH_4-N deposition was 24% and 30% lower in southern, 24% and 33% lower in central and 13% and 20% lower in northern Finland, respectively, than in the 1980s (Vuorenmaa 2003).

N_2O is a strong greenhouse gas, having a global warming potential of 296. In Finland, there have been no significant changes in N_2O emissions during the

Table 2: Beneficial and detrimental effects of reactive nitrogen (Cowling et al. 2001).

Direct effects on human health:
- increased yields and nutritional quality of the foods needed to maintain dietary requirements and food preferences for a growing population
- respiratory and cardiac disease induced by exposure to high concentrations of ozone and fine particulate matter
- nitrate and nitrite contamination of drinking water leading to the 'blue baby syndrome' and certain types of cancer
- blooms of toxic algae, with resultant injury to humans

Direct effects on ecosystems:
- increased productivity of N-limited natural ecosystems
- ozone-induced injury to crop, forest and natural ecosystems and susceptibility to attack by pathogens and insects
- acidification and eutrophication effects on forests, soils and freshwater aquatic ecosystems
- eutrophication and anoxia in coastal ecosystems
- N saturation of soils in forests and other natural ecosystems
- biodiversity losses in terrestrial and aquatic ecosystems and invasion by N-tolerant weeds
- changes in abundance of beneficial soil organisms that alter ecosystem functions

Indirect effects on other societal values:
- increased wealth and well-being of human populations in many parts of the world
- significant changes in patterns of land use
- regional hazes that decrease visibility at scenic vistas and airports
- depletion of stratospheric ozone by N_2O emissions
- global climate change induced by emissions of N_2O and formulation of tropospheric ozone
- damage to useful materials and cultural artefacts by ozone, other oxidants and acid deposition
- long-distance transport of reactive N, causing harmful effects in countries distant from emissions sources and/or increased background concentrations of ozone and fine particulate matter

In addition to these effects, it is important to recognize the following:
- the magnitude of the N flux often determines whether effects are beneficial or detrimental
- all of these effects are linked by biogeochemical circulation pathways of N
- reactive N is easily transformed among reduced and oxidized forms in many systems. N is easily distributed by hydrologic and atmospheric transport processes.

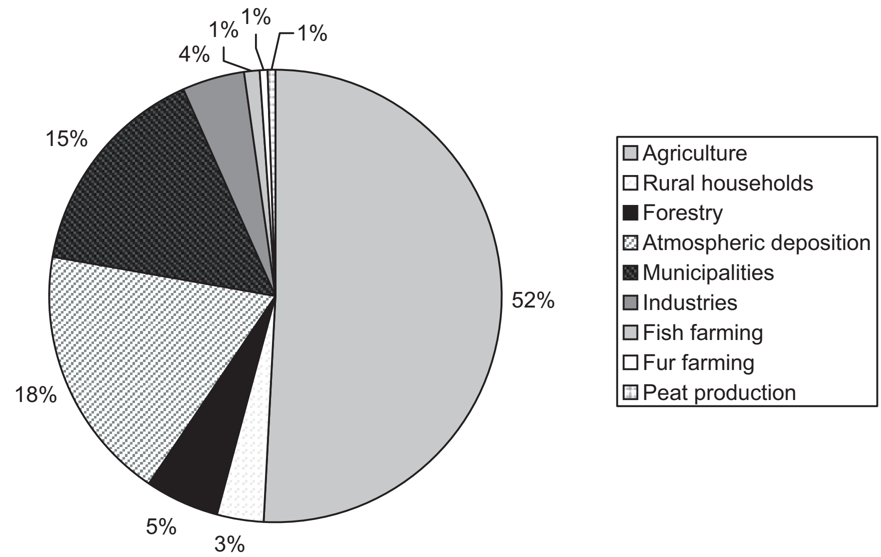


Fig. 4. N load to waters in Finland in 1990–2004 (Statistics Finland 2005a) .

1990s and early 2000s. The share of N_2O of Finnish greenhouse gas emissions (as CO_2 equivalents) was in 2005 approximately 18% (without land-use, land-use changes and forestry) or 10% (with land-use, land-use changes and forestry) (Statistics Finland 2007). Finland's target is to keep its greenhouse gas emissions at the 1990 level. Furthermore, Finland is committed to the EU target of reducing greenhouse gas emissions by 20% by 2020. In 2002, the Finnish greenhouse gas emissions exceeded the 1990 level by 6.8% (EEA 2005).

NO_2 is a precursor in formulation of tropospheric ozone. According to EEA (2005), ground level ozone concentrations are typically low in Finland and the few occurrences of elevated levels are due to long-range transport of emissions. The existing emission reduction targets are within reach.

1.3.2. Phosphorus (P)

Phosphorus is the eleventh most abundant mineral in the earth's crust, and ranks thirteenth in seawater. In contrast to N, the atmospheric flows of P are small because P does not form any long-lived gaseous compounds. Another significant difference is that, unlike N cycle, the P cycle is not dominated by biota, even though microbes and plants play an important role in assimilation, decomposition and mineralization of P. The two main types of phosphate rock deposits are igneous and sedimentary, and they have widely differing mineralogical, textural and chemical characteristics. The most abundant of the phosphate minerals is apatite.

In the pre-industrial era, the main source of P to the biological cycle was P weathering from soil. Bioavailable P was taken up by plants and bioaccumulated by animals, and released again for the use of plants when the organisms died and decomposed (Fig. 5). Erosion and water runoff transfer are important parts of the P cycle, and the eventual sink of particulate and soluble P is water sediments. Oceans form the largest biospheric P reservoir (Smil 2000).

Soil P can be divided into three main fractions: P in soil solution; P in the labile pool and P in the non-labile fraction (Mengel & Kirkby 1982). P in soil solution can be utilized by plants. The labile P fraction consists mainly of phosphate adsorbed to the surface of clay minerals, hydrous oxides, carbonates, apatites and Fe and Al phosphates. This fraction is in rapid equilibrium with the P in soil solution, soil pH being the most important factor influencing

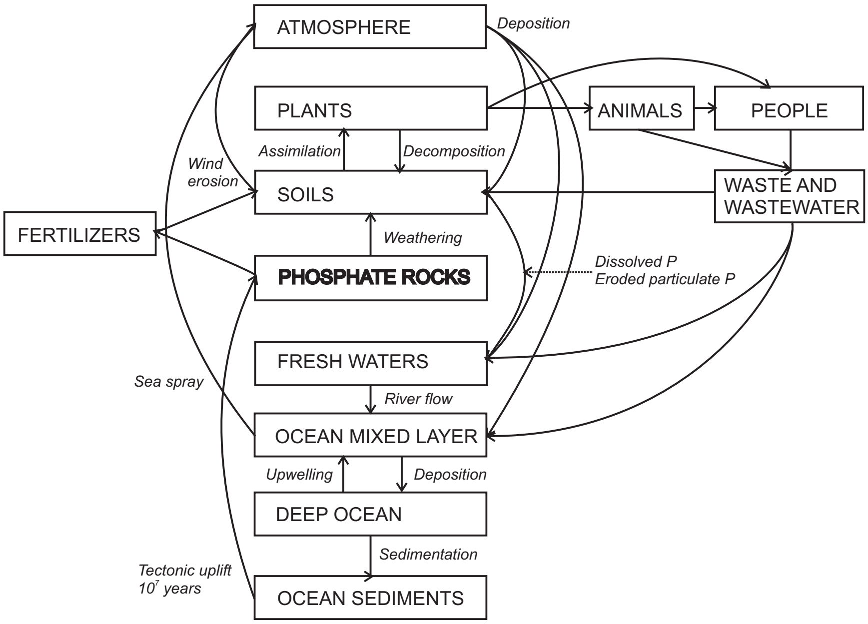


Fig. 5. Simplified global P cycle (based on Smil 2000).

the relationship between adsorbed P and P in soil solution. The amount of P present in soil solution is very low in comparison with adsorbed P.

Decomposition and mineralization of organic matter releases P back into soil solution. Microbial breakdown of soil organic matter is associated with increased CO_2 production, which possibly increase the solubility of phosphates (Mengel & Kirkby 1982).

P is the most immobile of the major nutrients, and P deficiency of agricultural soil is a general phenomenon. Fertilizers are applied to reduce the problem. Apatite is commonly used as a raw material for phosphate fertilizer production. Today, the annual global production of phosphate is around 40 million tonnes of P_2O_5, derived from roughly 140 million tonnes of rock concentrate. Mineral fertilizers account for approximately 80% of phosphates used worldwide, with the balance divided between detergents (12%), animal feeds (5%) and such speciality applications (3%) as food grade and metal treatment (Steen 1998).

Similarly to the cycles of N, the cycling of P has been greatly enhanced by humans. Smil (2000) estimated that human activities have roughly tripled the global P cycle compared with its natural flows. The major categories of human interferences in the P cycle are accelerated erosion and runoff owing to conversion of forests and grasslands, production and recycling of crop residues and manure, discharges of urban and industrial wastes and production of inorganic fertilizers. Bennett et al. (2001) estimated the net storage of P in terrestrial and freshwater ecosystems to be at least 75% larger than the pre-industrial levels of storage. They also found out that the rate of P accumulation is decreasing in developed nations, but increasing in developing countries.

As a consequence of intensified P use, its discharges and leaching to waters have increased. This, in turn, has in many places led to eutrophication. Eutrophication refers to an excess supply of nutrients, resulting in increased biological activity.

In waters, inorganic P is uptaken by plants and further enriched in the food chain. When the organisms die, they sink towards the bottom of water, where decomposition and mineralization take place. Depending on the oxygen conditions of the bottom area, P is either retained in sediment or released to water. For example, in the Gulf of Finland, the most eutrophicated part of the Baltic Sea, a large portion of the mobile pool of P in these sediments consists of iron (Fe)-bound P, which is released when

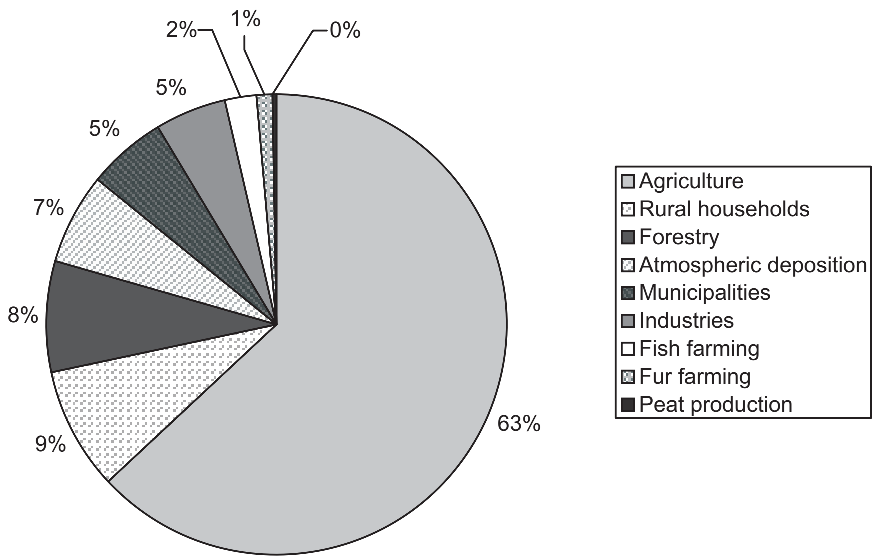


Fig. 6. P load to waters in Finland in 1990–2004 (Statistics Finland 2005a).

Fe(III) oxides are reduced under anoxic conditions (Lehtoranta 2003). Upwelling and annual turnover brigs P to the water surface, where it is again available for plants' primary production.

In Finland, the majority of lakes are oligotrophic, and thus, sensitive to changes in nutrient inputs. P is generally the growth-limiting minimum nutrient in fresh waters (Wetzel 1983). According to Pietiläinen and Kauppi (1993) and Pietilainen and Räike (1999), the primary production in Finnish lakes and in large rivers around lakes is limited by P. The production in rivers in coastal region is either limited by N or co-limited by N and P. In Finland, agriculture is the main source of P inputs to waters, followed by rural households and forestry (Fig. 6). Of the point sources, municipalities are the largest P source. According to the VAHTI emission database maintained by the Finnish environmental administration, the pulp and paper industry is the main source of industrial N and P discharge to waters.

Besides eutrophication, another problem related to intensified P cycling is the increasing utilization of P itself. Phosphate reserves are a non-renewable natural resource and the accelerating use of this raw material will eventually lead to depletion.

1.4. Study area – Finland

Finland is situated in northern Europe between the 60th and 70th parallels of latitude. Forests, inland waters and agricultural land formulate much of the Finnish landscape. Forest and other wooded land cover 68%, agricultural land 8%, and inland waters 10% of the country's area (Statistics Finland 2005a). Peatlands are an important part of Finnish nature, covering 34% of forestry land (FFRI 2001).

Substantial changes have occurred in Finnish society since the end of the 19th century. The Finnish population grew from 2.7 million in 1900 to 4.0 million in 1950 and further to 5.2 million in 2000 (Fig. 7). The urban proportion rose from only 13% in 1900 (Myllyntaus 1991) to 56% in 1960 and 82% in 2000 (Statistics Finland 2005a). The average population density is low, about 17 persons km^{-2}. However, in Southern Finland the population density is about 135 persons km^{-2}, as compared to approximately 2 persons km^{-2} in Northern Finland.

At the beginning of the 20th century, economic development in Finland was relatively low (Fig. 7). World War I caused a halt in economic development. The GDP did not reach the same level as before

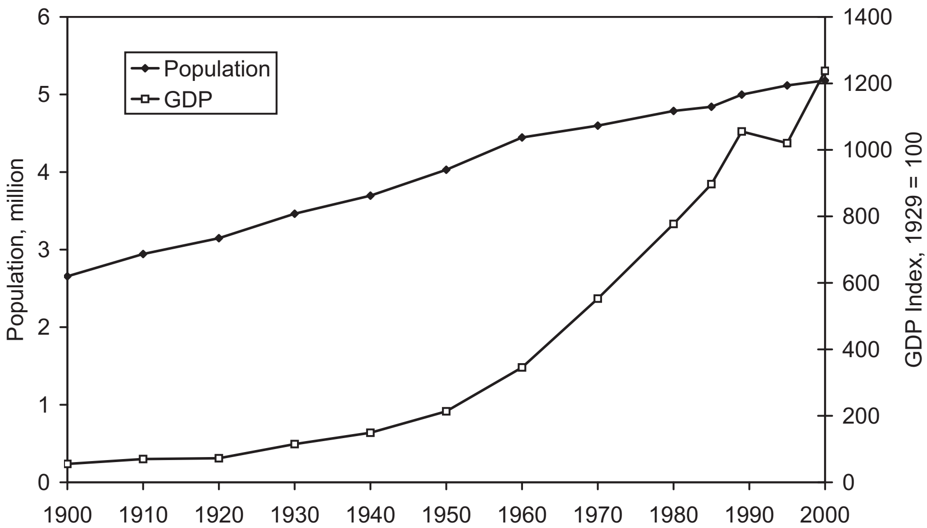


Fig. 7. Finnish population and gross domestic product (GDP, volume index) in 1900–2000 (Statistics Finland 2005a, 2005b).

World War I until 1922 (Kauppila 1999). However, in 1920–1938, the economic development was very fast, with average GDP growth of 4.7% per year. After World War II, GDP again grew rapidly, except during the oil crisis of 1973–1974 and the recession at the beginning of the 1990s.

At the beginning of the 1900s, agriculture was the prevailing production sector in Finland. Throughout the 20th century, its importance has decreased significantly, while the respective proportion of industries and services have grown. The share of agricultural and other primary production of the GDP fell from 60% in the early 1860s to 20% by the late 1950s. At the same time, the share of manufacturing and other secondary production rose from less than 20% to about 40%, and the share of the service sector from slightly over 20% to 40% (Hjerppe 1989). Currently, the services industry is the predominant sector in Finland (64% of GDP), while the significance of primary production is low (ca. 4% of GDP) (Statistics Finland 2005a).

Industrialization in Finland was largely based on the use of natural resources, wood and mineral products. Forest industry remains one of the main industrial sectors in Finland, but the industries that manufacture electrical and optical equipment have recently grown rapidly, becoming the leading industry branch (Statistics Finland 2006). Other key industrial sectors include production of machinery and equipment, chemicals and food and feed processing. When considering the flows of N and P, the chemical industry (mainly fertilizer production), forest industry and food and feed processing industry are the most important (Millennium Ecosystem Assessment 2005), and thus, the construction, metal and electrical industries are excluded from this study.

Agriculture

The field area in Finland grew from approximately 1.6 million hectares to over 2 million hectares at the beginning of the 1900s. Forest areas and marshes were cleared, and meadows and pastures were taken into field production. The loss of arable land after World War II (270 000 ha) resulted in a need for land clearing for cultivation in the middle of the 20th century. At that time, even peat soils with low fertility were taken under cultivation. The highest field area was in the 1960s (2.7 million ha), after which it decreased to the 2.2 million hectares. The number of farms has also decreased continuously since the 1960’s. The average farm size increased to 28 hectares in 2000.

In the first half of the 20th century, the prevailing cropping system was cultivation by rotating cereals and grass. Manure was initially the main nutrient supplement, but the use of especially P fertilizers

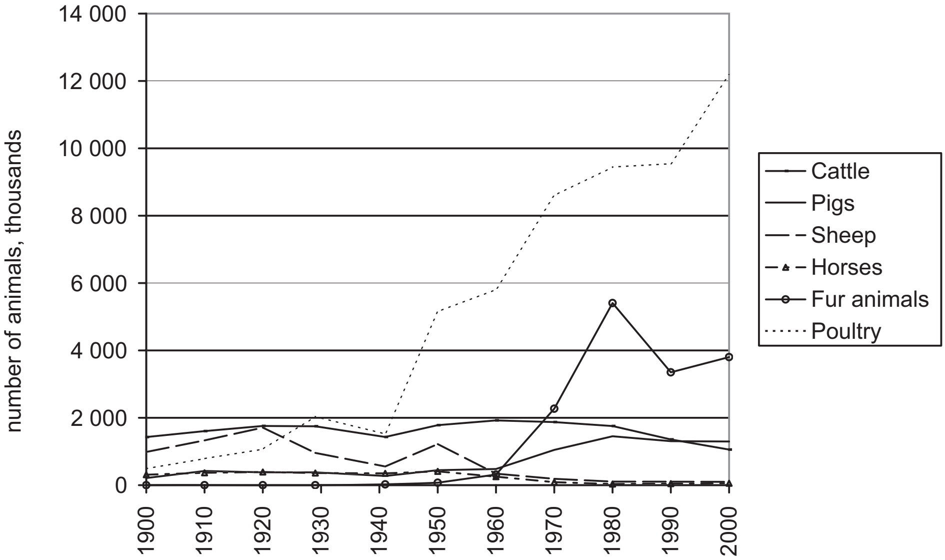


Fig. 8. Livestock in Finland, 1900–2000 (census of agriculture performed in 1910, 1920, 1929–1930, 1941, 1950 and 1960), Annual Statistics of Agriculture (1973, 1981), National Board of Agriculture (1992) and Information Centre of the Ministry of Agriculture and Forestry (2001)).

began to increase in the 1920s. Biological and technological developments (synthetic fertilizers, pesticides, plant breeding, cultivation techniques, etc.) led to an increase in crop yields. By the 1970s, the production of fodder crops (mainly barley) exceeded domestic consumption.

The area of different cereal crops changed during the 20th century. Fallow was important in crop rotation at the beginning of the century, but increased use of fertilizers and pesticides decreased its importance. In 1990, the acreage of fallow again increased as a result of agricultural policies and the need to reduce production. Meadows were cleared for arable land and hay production, and grazing moved to fields at the beginning of the 20th century.

Several extensive changes also occurred in animal husbandry during the 20th century. The numbers of horses and sheep decreased, and the numbers of pigs and poultry increased (Fig. 8). Fur farming was introduced and it is currently an integral part of Finnish animal production. Due to rapid progress in animal breeding and improved animal feeding, the production potential of farm animals has increased significantly (Maijala 1969, Juga et al. 1999).

In 1995, Finland joined the EU. The membership altered the control of food and feed chains from an administrative control to market control. However, Finnish agriculture is still strongly subsidized. The significance of subsidies in the Finnish agricultural income formation is larger than in other EU countries. The share of the environment subsidy of the total agricultural subsidy is significant (about 16–20%), and the environmental subsidy system has contributed to the development of the environmental protection in the agricultural sector. The environmental subsidy was not, however, the driving force behind environmental protection in Finnish agriculture; goals for nutrient leaching and biodiversity, for instance, were already in place (see e.g. Vesiasiain neuvottelukunta 1987, Finnish Ministry of the Environment 1992).

Other farm-related production activities in Finland include reindeer and fish farming. On a national scale, the significance of these sectors is relatively low, but in south-western coastal areas fish farms are significant source of nutrients to waters.

The food and feed processing industry is the fifth largest industrial sector in Finland (Statistic Finland

2006). The main sectors of the food processing industry are meat processing, bakeries, breweries and dairies. Approximately 85% of the raw materials are domestic.

Forests and forest industry

Most of Finland is located in the boreal forest zone, and forests are one of the most important natural resources of the country. The most common tree species are Scots pine (47% of the growing stock volume) and Norway spruce (34%). Broad-leaved species, mostly birch, represent 19% of the growing stock volume. Slash-and-burn cultivation, which persisted in some parts of Finland up to the early 1900s, had a long-lasting effect on the tree species composition and age structure of most forests in Finland (Reunala 1994, Leikola 1997).

At the end of the 1800s, sawing, woodland grazing, export of roundwood and ship construction were common. Wood consumption began to expand along with the development of a sawing technique using steam mills in the latter part of the 1800s (Ollonqvist 1998). Mechanical and chemical pulpwood industries as well as paper machines were developed at that time. Since the 1950s, consumption of roundwood has not increased at the same rate as the forest industrial production because non-industrial use of wood has decreased, and industrial wood consumption efficiency has increased as a result of technological and process changes. Since the mid-1990s, the import of wood has grown significantly, and currently, imported wood accounts for approximately one-fifth of the forest industries' wood consumption (Fig. 9). The imported wood is mainly birch from Russia.

The growing stock volume of the Finnish forests is ca. 2000 million m^3. Since the 1920s the growing stock volume has risen by approximately 25%. The annual increment of the growing stock has also continuously increased, currently being ca. 83 million m^3 a^{-1} (Fig. 10). The annual increment exceeds the total drain by about 13 million m^3 a^{-1}.

Fertilizer production

Chemical industries include production of fertilizers, explosives, plastics and fibres and paints, with fertilizers being the most important with regard to creating N and P flows (Febre Domene and Ayres 2001). The production of inorganic fertilizers in Finland began in 1922. Imported raw materials were initially used, but since 1980 Finnish apatite has replaced other raw materials. The Finnish apatite mine is the only such mine in Western Europe. Nitric acid is produced from ammonium to meet the needs of the fertilizer industry and the explosives industry. Since the late 1980s, ammonium has been imported.

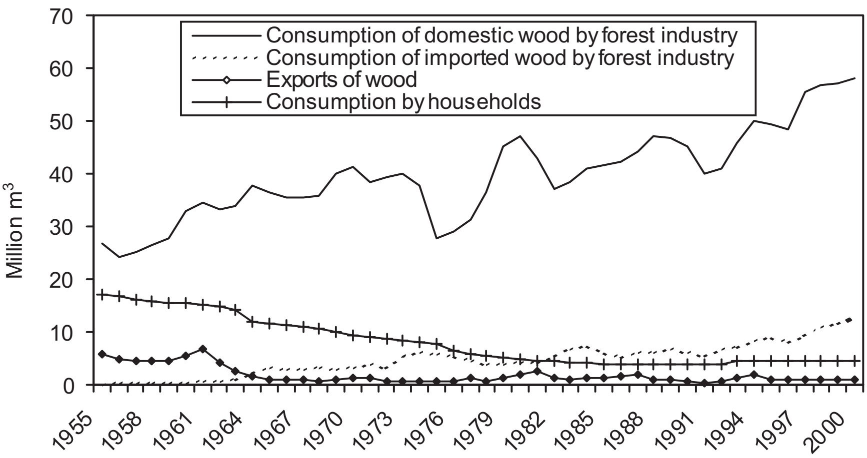


Fig. 9. Consumption of domestic and imported wood and export from Finland (FFRI 2001).

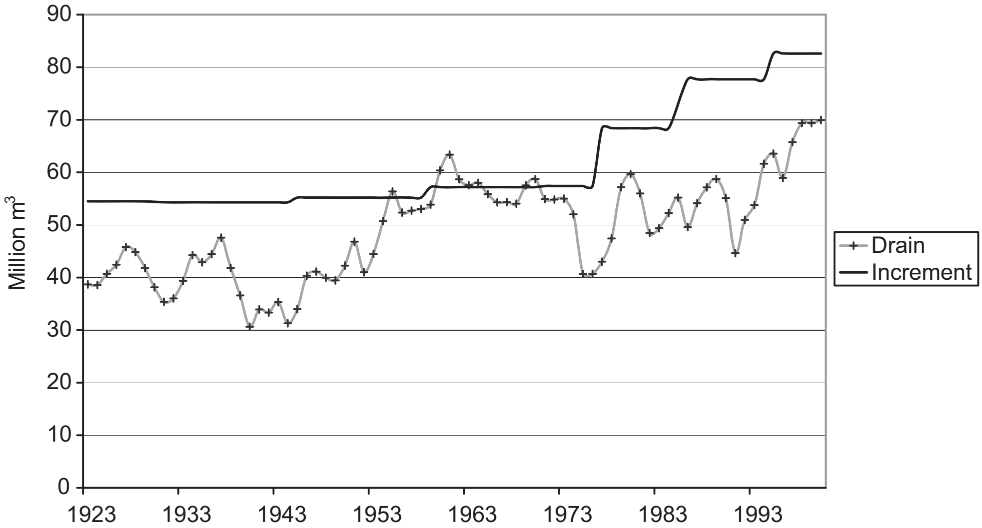


Fig. 10. Annual increment of forest growing stock and growing stock drain, 1923–2000 (Osara et al. 1948, Pöntynen 1962, FFRI 2001).

Energy production and consumption

In Finland, the specific energy consumption per capita is high due to the cold climate, the long transport distances and an energy-intensive industry. A high standard of living also increases the relative energy production. During the 20th century energy consumption has continuously increased (Fig. 11). In 1995–1999, total energy consumption in Finland grew from 1200 PJ to 1330 PJ. The largest consumer was industry (52% in 1999). Space heating accounted for 20% and transport for 14% of consumption (Statistics Finland 2001). The main energy source was oils, comprising 27% of the total energy consumption. Other large sources were wood fuels (20%), nuclear power (18%), coal (11%) and natural gas (10%) (Fig. 11).

Wood fuels were the main energy source in both industry and households in Finland at the turn of the 20th century. When World War I started, 90% of Finnish total energy was produced using wood fuels (Fig. 11). If transportation is excluded, the main energy sources remained domestic (wood fuels and water power) until the 1960s. Water power gained ground especially in the 1930s, when the need for electricity grew due to industrialization and technological development. The share of water power in electricity production increased, accounting for 70–80% of production from the 1930s to the 1960s (Nevanlinna 1993). Oil as an energy source grew significantly in the 1960s. However, the energy crisis in 1973–1974 led to a reduction in oil consumption, and alternative or supplementary energy sources were introduced. Utilization of natural gas and nuclear power began, and the consumption of peat and wood chips grew.

Transportation in Finland had not developed very much by the end of the 1800s. Animal power, especially horses, was widely used in agricultural work and transportation. Railway transportation in Finland began in 1862 and increased relatively rapidly. Already in 1914, two-thirds of the existing Finnish railways were built. Locomotives used wood until 1897, after which coal burning was instigated. Steam locomotives were changed to diesel locomotives in the 1940s. Since 1968, the railways have been electrified. Cars were introduced in the 1920s, but their proportion increased slowly. Between the 1950s and the 1990s, the number of cars grew quickly. In 2000, there was 0.41 car per inhabitant (Statistics Finland 2005a). Air transport has also grown significantly, from 0.9 million passenger trips in 1960 to 13.8 million passenger trips in 2000.

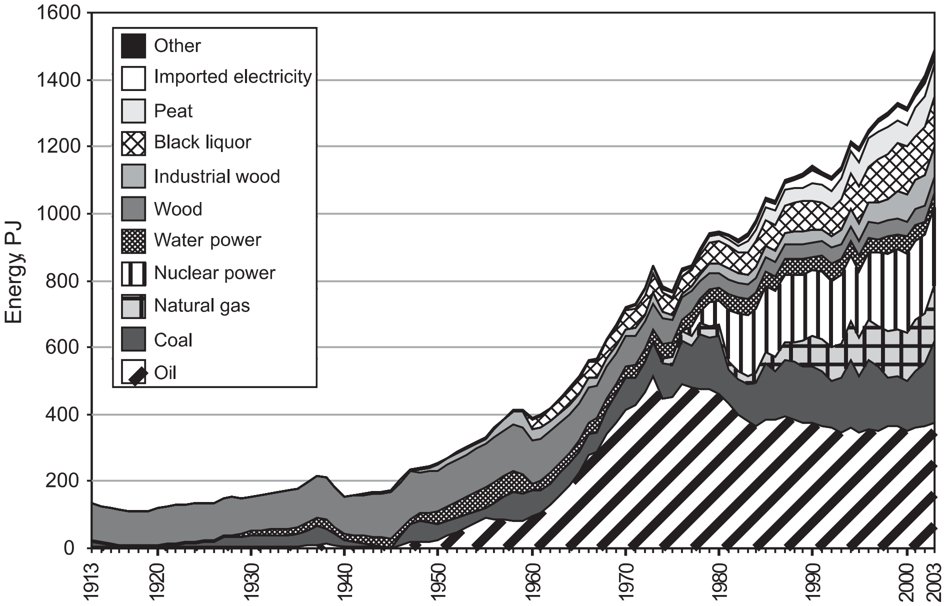


Fig. 11. Total energy consumption in Finland by energy source in 1913–2003. Sources: 1913–1959, Myllyntaus (1980); 1960–1969, Ministry of Trade and Industry in Finland (1977); 1970–2003, Statistics Finland (2004).

2. Aims of the study

Increased production and consumption have intensified N and P cycles and led to such environmental problems as eutrophication, acidification and climate change. In Finland, agriculture is known to be the main source of nutrient load to the waters, followed by municipalities, rural population and pulp and paper industries (Statistics Finland 2005a). Transportation and energy production cause the largest emissions of N to air (Statistics Finland 2004). However, an analysis that systematically studies the cycles of N and P in different societal sectors in Finland has been lacking. A deeper understanding of the sources, flows and possible openness of the N and P cycles is important when assessing ways to reduce nutrient emissions to the environment.

The flows and stocks of nitrogen (N) and phosphorus (P) in Finland were investigated in the following four subsystems: (I) forest industry and use of wood fuels, (II) food production and consumption, (III) energy and (IV) municipal waste. The aim was to identify and quantify the main flows of N and P in Finland in these systems. Past changes in the N and P flows were also examined. The municipal waste and energy systems were used as examples for the historical study. These systems were chosen because their historical changes have rarely been assessed in other N and P flow studies.

Specific aims of this study were to answer the following questions:

1. What are the largest N and P flows in Finland in the systems studied?
2. To what extent are the nutrient systems cyclic or linear?
3. How could these systems be more efficient in the use and cycling of N and P?
4. How can this type of analysis be used to support decision-making on environmental problems?

3. Materials and methods

Substance flow analysis (SFA) was used as the main method to calculate the N and P flows in the four subsystems studied in Finland.

3.1. Substance flow analysis (SFA)

SFA is applied to analyse the flows and stocks of a single substance or a coherent group of substances (van der Voet 2002). This type of analysis covers all the actions in a studied system, including the extraction or harvesting of material resources, chemical transformation, manufacturing, consumption, recycling and the final disposal of materials. The substances being examined can be elements, such as N, carbon or lead, or compounds, such as polycyclic aromatic hydrocarbons (PAHs). SFA can be classified as a subcategory of material flow analysis (MFA), which investigates bulky materials, such as wood or minerals, flowing through a specific system, rather than a single substance.

Studies that can be classified as SFA applications have been conducted since the 1920s, first in ecology. Studies on biogeochemical cycles, including human interference, and on flows in economic systems were performed later. More harmonized SFA efforts began in the 1990s (van der Voet 2002).

SFA studies have been performed over a wide range of substances and over different spatial and temporal scales. N has gained a lot of attention. Its global cycle has been analysed by, for example, Galloway (1998), Smil (1999) and Galloway and Cowling (2002). Moreover, regional N flow analyses have been conducted, among others, by van der Voet et al. (1996) in the European Union, Egmond et al. (2002) in Europe and Zheng et al. (2002) in Asia. Nation-level N studies have been carried out as well by Olsthoorn and Fong (1998) in the Netherlands and Jordan and Weller (1996) and Howarth et al. (2002) in USA. Febre Domene and Ayres (2001) have also examined N flows in USA, but have concentrated on the industrial system. Another main nutrient, P, has drawn less interest. It has been analysed by, for instance, Brunner et al. (1994) in Switzerland, Nilsson (1994) in a Swedish municipality and Gransted (2000) in the Swedish agricultural ecosystem. The studies of the biogeochemical cycles of P by Smil (2000) and the global P cycles by Bennett et al. (2001) can also be classified as SFA studies.

Flows of different metals (e.g. lead, zinc, cadmium, chromium, copper, silver) have been investigated in Europe by Lanzano et al. (2006), in the European Community by van der Voet et al. (1994), in the Netherlands by Guinée et al. (1999) and in Stockholm, Sweden, by Palm and Östlund (1996) and Bergbäck et al. (2001). Chlorine has also been studied (Ayres 1997b, 1998; Ayres and Ayres 1997, 2000).

SFA can serve such purposes as identifying problem flows, economic leaks or inefficiencies in materials use in a given year, and pinpointing potential future problems (van der Voet et al. 1995; van der Voet 2002). Changes in flows and stocks over the years can also be monitored. The causes of environmental problems can be analysed by tracing problem flows or stocks to their origins. Moreover, the effectiveness of pollution abatement measures or the side-effects of other influencing measures on environmental problems can be estimated. Dynamic models can predict the anticipated effects of new abatement measures, and the time needed for the measures to become effective.

Most of the SFA studies conducted can be classified as bookkeeping systems, probably because static and dynamic modelling requires a substantial amount of time and resources. Dynamic SFA modelling has been performed by Kleijn et al. (2000) for PVC in Sweden. The study was, however, a theoretical example aimed at discussing some possibilities for estimating future outflows on the basis of information on current stocks. It must be borne in mind that none of the modelling levels is superior to the others, but the level applied in each case depends on the specific purpose of the study and its results.

3.2. System description

The borders of Finland are the spatial system boundaries of this study. Imports and exports of goods and the emissions of N and P are included as inputs and outputs. N here refers to reactive N. If elementary nitrogen (N_2) is considered, it is separately mentioned. The amount of N and P in different stocks and flows was calculated as total N and P.

A detailed analysis of the N and P flows in Finland at the end of the 1990s was performed for four subsystems:

I. Forest industry and use of wood fuels (Fig. 13, Paper I),
II. Food production and consumption system (Fig. 14, Paper II),
III. Energy system (Fig. 15, Paper III) and
IV. Municipal waste system (Fig. 16, Paper IV).

These systems are known to be the most important for human-introduced N and P flows (see Ayres et al. 1994, Vitousek et al. 1997, Smil 2002, Millennium Ecosystem Assessment 2005). The overview of the systems and main flows analyzed is presented in Fig. 12.

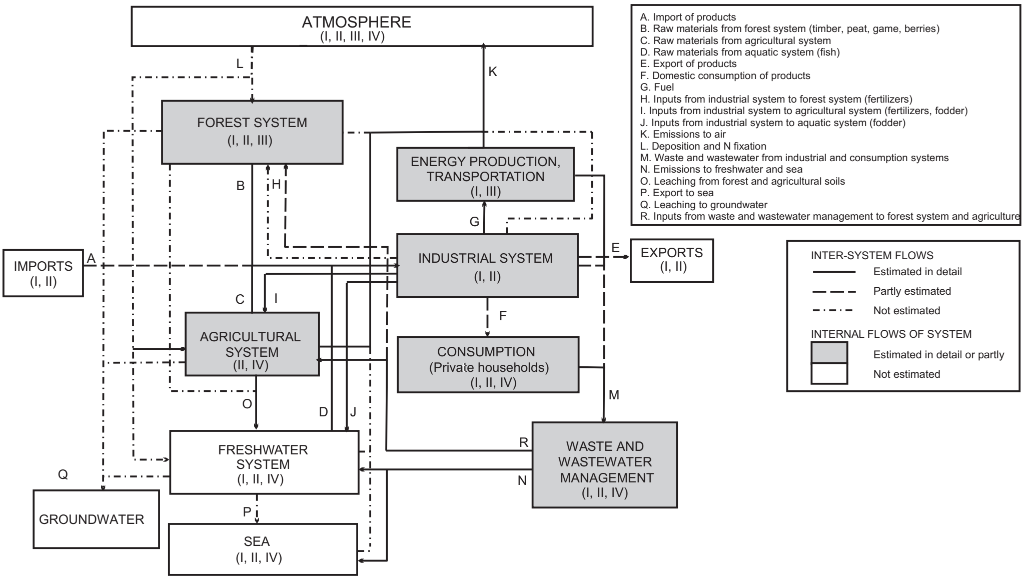


Fig. 12. Overview of the analyzed system, presented in more detail in Figs. 13–16. Roman numbers refer to the Paper in which the flow is analyzed.

Whenever possible, an annual average of the N and P flows in 1995–1999 was calculated to represent the situation at the end of the 1990s. Emission data sorted by fuel sources were unavailable before the year 2000. Thus, the detailed analysis of the energy system was carried out using the year 2000 as a reference.

Historical development of N and P flows in municipal solid waste and energy systems were analysed. Municipal waste system flows were analysed starting from 1952 and energy system nutrient flows starting from 1900. The geographical borders of the study area changed after World War II, when Finland lost 13% of its total area to Soviet Union.

I Forest industry and use of wood fuels

In the subsystem of forest industry and use of wood fuels, the flows of N and P through the Finnish forest industry to consumption and wastes were examined (Fig. 13). The analysis also covers the foreign trade of the forest industry's raw materials and products and the use of wood-based fuels in energy production.

N and P are common elements in various chemicals such as resins, paper chemicals and wastewater treatment chemicals. Here, the chemicals were taken as inputs to the system; more detailed analysis of the chemical cycles was beyond this scope of the study. The chemicals enter the Finnish nutrient cycle via either imports (N, P) or excavation of soil (P) and leave the system in products, in emissions to air or water or in waste.

Emissions to water and air from the forest sector were analysed. The forest sector causes N emissions to air in several ways; when felling and transporting the trees, in industrial processes and in transporting the products. Our analysis is limited to emissions from wood fuels, i.e. emissions from fossil fuels were excluded.

II Food production and consumption system

In subsystem II, the stocks and flows of N and P in the Finnish food production and consumption system were identified and quantified (Fig. 14). Atmospheric deposition, biological N fixation and imports of food products were considered as nutrient inputs to the system. Exports and emissions to waters and air were considered as outputs from the system. Domestic food production was also analysed. Fur farming was investigated as part of the agricultural system. Nutrient leaching to groundwater was not

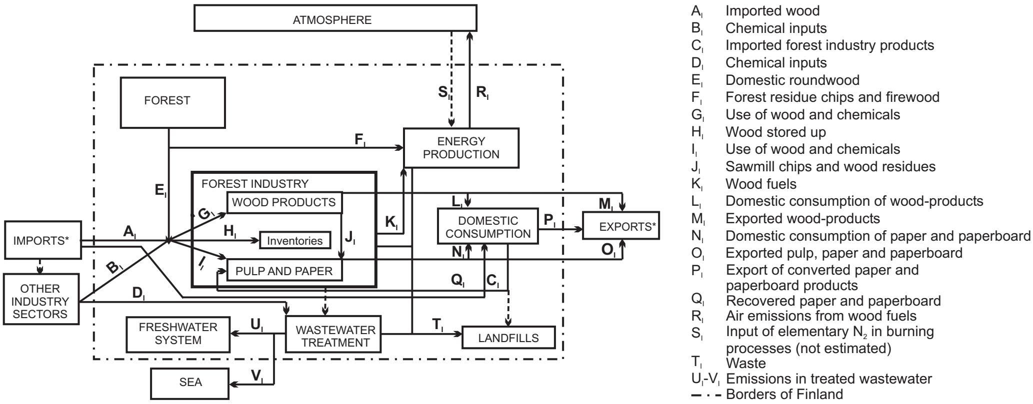


Fig. 13. Flows of N and P in the Finnish forest industry and use of the wood fuels system (Paper I). *Imports and exports do not include secondary products, e.g. packaging materials.

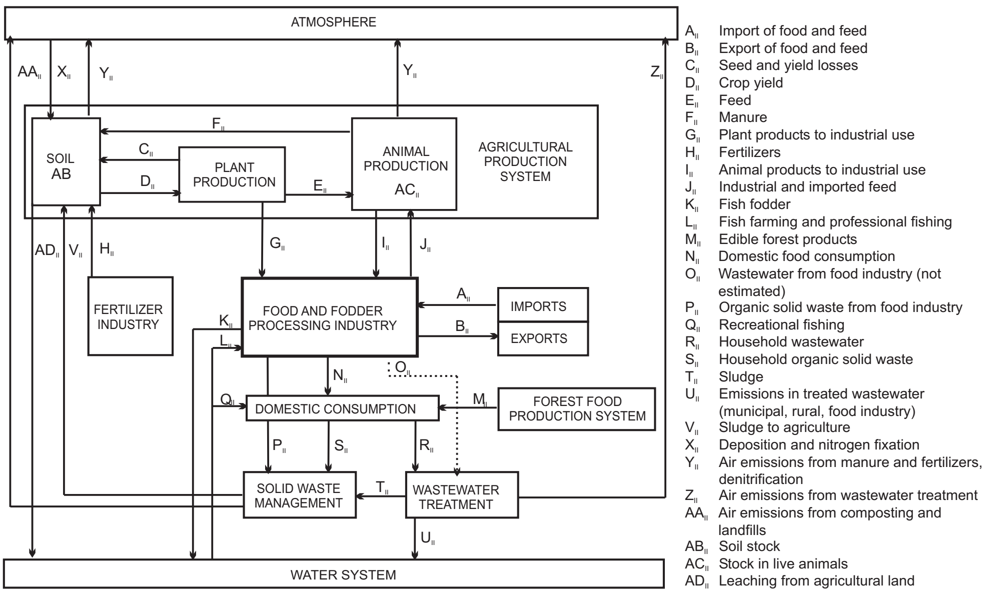


Fig. 14. Flows of N and P in the Finnish food production and consumption system (Paper II).

considered due to data limitations. Fertilizers were included as inputs to the system; a more detailed analysis (import, export and production) of them was beyond the scope of this study.

III Energy system

The energy system analysed here covers the combustion of fuels inside the Finnish borders. Nutrients enter the energy system from the forest system (wood, peat) or in fuels imported from outside the Finnish borders (coal, oil, natural gas) (Fig. 15). In addition, some nutrients come from the waste system inside the human economy.

In combustion, all N in the fuel is released to the air. The N in the organic molecules of fuel is called "fuel N". During combustion, both fuel N and N from combustion air (N_2) are transformed

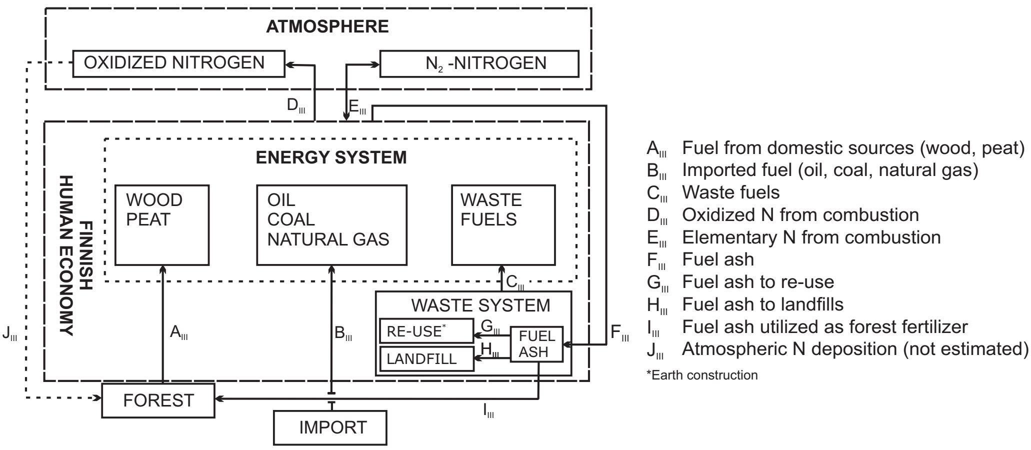


Fig. 15. Flows of N and P in the Finnish energy system (Paper III). The flow of oxidized N back to the forest (atmospheric deposition) was not estimated.

into emissions of N oxides (NO_x) or nitrous oxides (N_2O). However, N can leave the energy system after combustion also as harmless molecular N_2. Emissions of inert molecular N_2 from combustion are irrelevant compared with the vast amount of N_2 (78%) in the air.

After combustion, P remains in the fuel ash, ending up in the human economy in landfills or in construction industries, or is released to the environment in ash fertilizers.

IV Municipal waste system

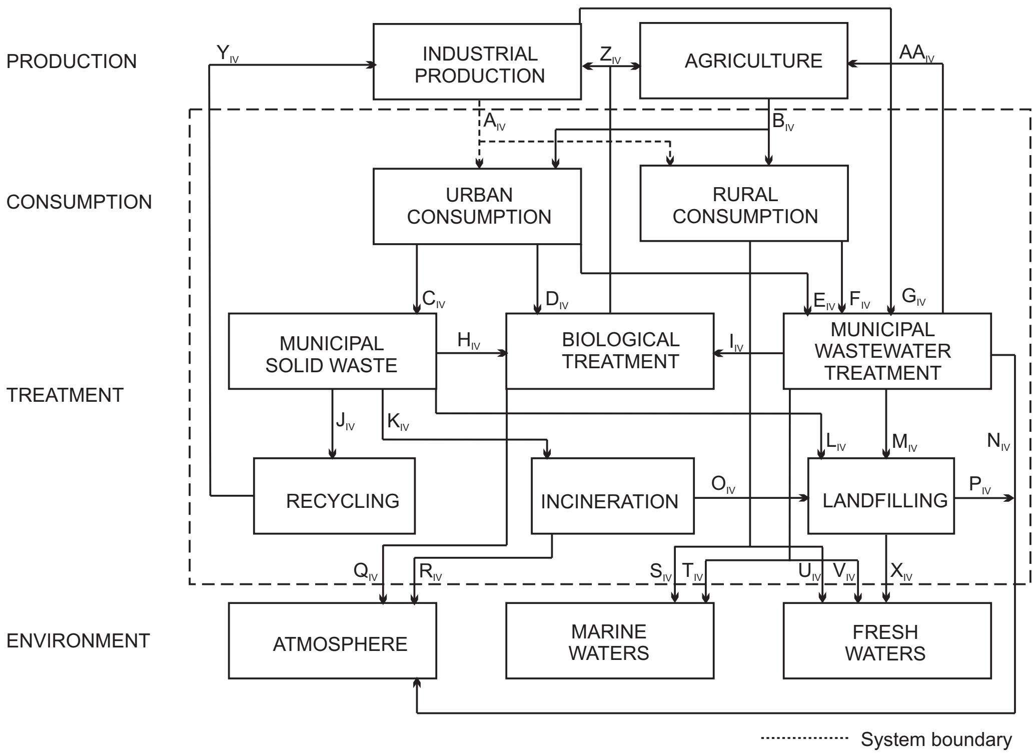
The municipal waste system encompasses municipal and rural wastewaters and solid waste (Fig. 16). Municipal sewage sludges originating from municipal wastewater treatment form an important part of the system. The term municipal solid waste refers to all the miscellaneous waste, such as kitchen waste, yard trimmings, waste paper and packaging, that is treated in the municipal waste management system.

Nutrients enter the municipal waste management system through private consumption of products from the industrial and agricultural sectors. In the municipal waste management system, nutrients are treated in one of the four different pathways: recycling, biological treatment (i.e. composting and anaerobic treatment), incineration or landfill deposition. Some of the material is also returned to production. Loss of nutrients from the waste management system into the environment can occur either through aqueous emissions from municipal wastewater treatment plants, wastewaters from rural areas, landfill leachates and leaching from compost fields (not assessed in this study due to low data availability) or through gaseous emissions from biological treatment, wastewater treatment, incineration and landfills. Nutrient emissions to water and air and recycled nutrients were examined as outputs from the municipal waste management system. In the surveyed time period, landfills were considered as sinks of nutrients.

3.3. Data sources and quantification methods

3.3.1 Situation at the end of the 1990s

Official statistics, environmental emission monitoring data, literature about the nutrient concentrations in different products and expert estimates provided the basis for calculation of the nutrient flows. Information on the quantification of the nutrient stocks and flows is given in Table 3 and Papers I–IV.



A_{IV}: Industrial products to consumption (not estimated); B_{IV}: Agricultural products to consumption; C_{IV}: Municipal solid waste; D_{IV}: Biological treatment of household waste at source; E_{IV}: Municipal wastewater; F_{IV}: Sediment basin sludge; G_{IV}: Industrial wastewater and wastewater treatment chemicals; H_{IV}: Biological treatment of municipal solid waste; I_{IV}: Biological treatment of sewage sludge; J_{IV}: Separately collected recycling paper; K_{IV}: Incineration of solid waste; L_{IV}: Landfill deposition of solid waste; M_{IV}: Landfill deposition of sewage sludge; N_{IV}: Emissions to air from wastewater treatment (incl. anaerobic stabilization of sewage sludge); O_{IV}: Landfill deposition of incineration ashes; P_{IV}: Emissions to air from landfill deposition; Q_{IV}: Emissions to air from biological treatment R_{IV}: Emissions to air from incineration; S_{IV}, U_{IV}: Rural household wastewater discharges; T_{IV}, V_{IV}: Municipal wastewater discharges; X_{IV}: Leaching from landfills; Y_{IV}: Recovery of recycled paper; Z_{IV}: Utilization of biologically treated municipal waste (incl. sewage sludge); AA_{IV}: Utilization of sewage sludge

Fig. 16. Flows of N and P in the Finnish municipal waste system (Paper IV).

Wood consumption in the forest industry and the emissions to water are also analysed regionally. The nine regions used are the following aggregates of Finnish regional councils (see also Paper 1, Fig. 3):

1 = Uusimaa and East Uusimaa
2 = Southwest Finland and Satakunta
3 = Häme, The Tampere Region, Päijät-Häme and Central Finland
4 = South Ostrobothnia, Ostrobothnia and Central Ostrobothnia
5 = Kymenlaakso and South Karelia
6 = South Savo, North Savo and North Karelia
7 = Oulu Region and Kainuu
8 = Lapland
9 = Åland

Table 3a: Data sources and quantification methods of N and P flows in 1995–1999 in the Finnish forest industry and use of the wood fuels system (Paper I).

Flow		**Data source**
I Forest industry and use of wood fuels		
A_I	Imported wood	• Statistical Yearbook of Forestry (FFRI 1996, 1997, 1998, 1999, 2000), METINFO 2002
B_I	Chemical inputs	• Foreign trade and production statistics (National Board of Customs 1997, 1998, 1999, 2000, 2001; Statistics Finland 2002); • Personal communications (J. Rainio, Dynea Overlays Inc., Jan. 2002; R. Kauppi, Dynea Finland Inc., Jan. 2002; M. Hasanen Finnforest Inc., May 2002); • Chemical use information (Nurmi and Heikkilä 1996, 1997; Nurmi et al. 1998; Heikkilä and Nurmi 1999; Niemelä and Nurmi 2000)
C_I	Imported forest industry products	• See A_I; Foreign trade statistics (National Board of Customs 1997, 1998, 1999, 2000, 2001)
D_I	Chemical inputs	• Environmental statistics of forest industries (FFI 1996, 1997, 1998, 1999, 2000) • Personal communications (T. Jouttijärvi, SYKE, May 2002; A. Orkola, Kemira Inc., Jan. 2002)
E_I	Domestic roundwood	• See A_I
F_I	Forest residue chips and firewood	• Energy statistics (Statistics Finland 2001)
G_I	Use of wood and chemicals	• See A_I, B_I, E_I
H_I	Stored wood	• See A_I
I_I	Use of wood and chemicals	• See A_I, B_I, E_I
J_I	Sawmill chips and wood residues	• See A_I
K_I	Wood fuels	• See F_I
L_I	Domestic consumption of wood products	• Residue
M_I	Exported wood products	• Statistical Yearbook of Forestry (FFRI 1996, 1997, 1998, 1999, 2000) • Foreign trade statistics (National Board of Customs 1997, 1998, 1999, 2000, 2001)
N_I	Domestic consumption of paper and paperboard	• Residue
O_I	Exported pulp, paper and paperboard	• Statistical Yearbook of Forestry (FFRI 1996, 1997, 1998, 1999, 2000)
P_I	Export of converted paper and paperboard products	• See O_I
Q_I	Recovered paper and paperboard	• See O_I
R_I	Air emissions from wood fuels	• Air emission data (Finnish Environment Institute 2003)
S_I	Input of elementary N_2 in burning processes	• Not estimated
T_I	Waste	• Environmental statistics of forest industries (FFI 1996, 1997, 1998, 1999, 2000)
U_I, V_I	Emissions in forest industry's treated wastewater	• Environmental emission monitoring data (VAHTI database)

Table 3b: Data sources and quantification methods of N and P flows in 1995–1999 in the Finnish food production and consumption system (Paper II).

II Food production and consumption system		
A_{II}	Import of food and feed	• Foreign trade statistics (National Board of Customs 1997, 1998, 1999, 2000, 2001)
B_{II}	Export of food and feed	• See A_{II}
C_{II}	Seed and yield losses	• Seed: the balance sheet for food commodities (Information Centre of the Ministry of Agriculture and Forestry 1996a, 1997a, 1998a, 1999a, 2000a); • Spoilage of silage and green fodder was assumed to be 10% and spoilage of hay 5%.
D_{II}	Crop yield	• Cultivated area and yield of the most important crops in Finland (Information Centre of the Ministry of Agriculture and Forestry 1996b, 1997b, 1998b, 1999b, 2000b); literature on dry weights and N and P concentrations (see Paper II, Table 1)
E_{II}	Feed	• Horses, suckler cows, growing cattle, sheep, boars, sows, goats and fur animals: feeding allowances (Tuori et al. 2002) and the proportions of different feeds (Komulainen 1997; Finnish Fur Breeders Association 2000); • Dairy cows: the feed consumption data in the Finnish milk recording system (Kytölä 2002); • Growing pigs, broilers and turkeys: the feed allowances needed to produce an animal suitable for slaughter (Kyntäjä et al. 1999; Ross 2002a; BUTT 2002); • Laying and breeding hens and growing pullets (Lohmann 2002, Ross 2002b)
F_{II}	Manure	• E_{II}–I_{II}
G_{II}	Plant products to industrial use	• Balance sheet for food commodities (Information Centre of the Ministry of Agriculture and Forestry 1996a, 1997a, 1998a, 1999a, 2000a); dry weights and N and P concentrations of plant products literature (see Paper II, Table 1)
H_{II}	Fertilizers	• Fertilizer sales statistics (Information Centre of the Ministry of Agriculture and Forestry 2000b, Ettala, Tigoteam Ltd., unpublished information); cultivation area of greenhouse plants (Information Centre of the Ministry of Agriculture and Forestry 2000b), consumed water quantity in greenhouses and water nutrient concentration (Grönroos and Nikander 2002)
I_{II}	Animal products to industrial use	• Annual average number of live animals, slaughtered animals and animal products (Information Centre of the Ministry of Agriculture and Forestry 1995, 1996b,c, 1997b,c, 1998b,c, 1999b,c, 2000b,c); N and P concentrations of the most important animals (Anon. 1985, Poulsen et al. 1998, Tuori et al. 2002, National Public Health Institute 2001)
J_{II}	Industrial and imported feed	• Official import and export statistics; balance sheet for food commodities (Information Centre of the Ministry of Agriculture and Forestry 1996a, 1997a, 1998a, 1999a, 2000a)
K_{II}	Fish fodder	• Reports by fish farmers on the amount of fodder consumed in farming and the separate reports of the Provincial Government of Åland; Wideskog (2000)
L_{II}	Fish farming and professional fishing	• Official statistics (Finnish Game and Fisheries Research Institute 2001)

M_{II}	Edible forest products	• Berry and mushroom crops and bags of game: official statistics (FFRI 2000); household consumption of berries: Mäenpää et al. (2000)
N_{II}	Domestic food consumption	• Balance sheets for food commodities (Information Centre of the Ministry of Agriculture and Forestry 1996a, 1997a, 1998a, 1999a, 2000a). N and P concentrations for different food and feed products: the food composition database (National Public Health Institute 2001), the nutritional value of feed database (Tuori et al. 2002) and Anon (1985), see also Paper II; Tables 1 and 2.
O_{II}	Wastewater from food industry	• Not estimated
P_{II}	Organic solid waste from food industry	• Animal derived by-products (Salminen 2002); nutrient concentrations of animals (see I_{II}). • Plant derived by-products: data on industrial use of plant products (Information Centre of the Ministry of Agriculture and Forestry 1996a, 1997a, 1998a, 1999a, 2000a); literature on dry weights and N and P concentrations (see Paper II, Tables 1 and 3)
Q_{II}	Recreational fishing	• Official statistics (Finnish Game and Fisheries Research Institute 2001)
R_{II}	Household wastewater	• See E_{IV}, $F_{IV,}$ $S_{IV,}$ U_{IV}
S_{II}	Household organic solid waste	• See D_{IV}, H_{IV}
T_{II}	Sludge	• See I_{IV}, M_{IV}, AA_{IV}
U_{II}	Emissions in treated wastewater (municipal, rural, food industry)	• Environmental emission monitoring data (VAHTI database), Paper III
V_{II}	Sludge to agriculture	• See AA_{IV}
X_{II}	Deposition and N fixation	• N deposition: regional deposition model DAIQUIRI (Syri et al. 1998, Kangas and Syri 2002). Land use types from the SLICES data (Separated Land Use/Land Cover Information System) (Sucksdorff and Teiniranta 2001) • P deposition: bulk deposition monitoring data (Vuorenmaa et al. 2001), area of agricultural land • Biological N fixation: N content of pea yield (Høgh-Jensen et al. 1998) plus the amount of N fixed by the clover-grass swards in organic farming (Väisänen 2000) plus associative N fixation (Haahtela 1986; Haahtela and Korhonen 1983)
Y_{II}	Air emissions from manure and fertilizers, denitrification	• N_2O losses: the greenhouse gas emission inventory to the European Commission (Finnish Ministry of the Environment 2002) • NH_3 losses from synthetic fertilizers: Keränen and Niskanen (1987), Pipatti et al. (2000) • Denitrification: Stevens et al. (1998), Bronson and Fillery (1998), Wolf and Russow (2000) • NH_3 from animals: Grönroos et al. (1998)
Z_{II}	Air emissions from wastewater treatment	• See N_{IV}
AA_{II}	Air emissions from composting and landfills	• See P_{IV}, R_{IV}
AB_{II}	Soil stock	N_{tot} and plant-available P, top 20 cm soil layer • distribution of Finnish soil types (Kähäri et al. 1987); • N_{tot} (Kaila 1948; Sippola 1981); • plant-available P (Mäntylahti 2002)
AC_{II}	Stock in live animals	See I_{II}
AD_{II}	Leaching from agricultural land	• Vuorenmaa et al. (2002); area of agricultural land

Table 3c: Data sources and quantification methods of N and P flows in 1995–1999 in the Finnish energy system (Paper III).

III Energy system		
A_{III}	Fuel from domestic sources	• Energy content of consumed fuels: energy, trade, import, and forest statistics (Paper III, Table 1); • Fuel properties literature (Paper III, Table 2); • Conversion coefficients for energy units and net heat contents: Statistics Finland (2004)
B_{III}	Imported fuel	• See A_{III}
C_{III}	Waste fuels	• Not included due to low importance (Saikku 2004)
D_{III}	Oxidized N from combustion	• Mäkelä et al. (2000, 2003); Finnish Environment Institute (2003); Statistics Finland (2004)
E_{III}	Elementary N from combustion	• Residual (calculated from A_{III}–D_{III})
F_{III}	Fuel ash	• All P assumed to stay in the ashes after incineration, and all N assumed to evaporate to air during combustion
G_{III}	Fuel ash to re-use	• F_{III}; Statistics Finland (2005c)
H_{III}	Fuel ash to landfills	• See G_{III}
I_{III}	Fuel ash utilized as forest fertilizer	• Own estimation in Paper I
J_{III}	Atmospheric N deposition	• Not estimated

Table 3d: Data sources and quantification methods of N and P flows in 1995–1999 in the Finnish municipal waste system (Paper IV).

IV Municipal waste system		
A_{IV}	Industrial products to consumption	• Not estimated
B_{IV}	Agricultural products to consumption	• See G_{II}, I_{II}, N_{II}
C_{IV}	Municipal solid waste	• Literature on solid waste generation and composition, see Paper IV, Tables 1 and 2
D_{IV}	Biological treatment of household waste at source	• Literature on solid waste disposal and composition, see Paper IV, Tables 1 and 2
E_{IV}	Municipal wastewater	• Environmental emission monitoring data (VAHTI database)
F_{IV}	Sediment basin sludge	• See E_{IV}
G_{IV}	Industrial wastewater and wastewater treatment chemicals	• See E_{IV}; information on nutrient load per capita (Finnish Ministry of the Environment 2001)
H_{IV}	Biological treatment of municipal solid waste	• See D_{IV}
I_{IV}	Biological treatment of sewage sludge	• Lapinlampi and Raassina (2002)
J_{IV}	Separately collected recycling paper	• See D_{IV}
K_{IV}	Incineration of solid waste	• See D_{IV}
L_{IV}	Landfill deposition of solid waste	• See D_{IV}
M_{IV}	Landfill deposition of sewage sludge	• Lapinlampi and Raassina (2002)
N_{IV}	Emissions to air from wastewater treatment (incl. anaerobic stabilization of sewage sludge)	• Personal communication (P. Rantanen, SYKE, Nov. 2002)

O_{IV}	Landfill deposition of incineration ashes	• All P assumed to stay in the ashes after incineration, and all N assumed to evaporate to air during combustion
P_{IV}	Emissions to air from landfill deposition	• Estimated on the basis of Tanskanen (1992)
Q_{IV}	Emissions to air from biological treatment	• Estimated on the basis of Saari et al. (1985) and Pipatti et al. (1996)
R_{IV}	Emissions to air from incineration	• All N assumed to evaporate to air during combustion
$S_{IV,}$ U_{IV}	Rural household wastewater discharges	• Official statistics (Statistics Finland 1999)
$T_{IV,}$ V_{IV}	Municipal wastewater discharges	• Environmental emission monitoring data (VAHTI database)
X_{IV}	Leaching from landfills	• Estimate based on Helsinki Metropolitan Area Council (1991) and Ettala et al. (1988)
Y_{IV}	Recovery of recycled paper	• Personal communication from I. Löfström, Paperinkeräys Oy, Oct. 2002
Z_{IV}	Utilization of biologically treated municipal waste (incl. sewage sludge)	• N: $H_{IV} + I_{IV} – O_{IV}$ • P: $H_{IV} + I_{IV}$
AA_{IV}	Utilization of sewage sludge	• Lapinlampi and Raassina (2002)

3.3.2. Historical data

Historical development of N and P flows was investigated in the energy and municipal waste systems. Energy system nutrient flows were analysed starting from 1900 and the municipal waste system flows starting from 1952. Here, an overview of the calculation of the historical development of N and P flows in energy and municipal waste system is given. Detailed data sources and quantification methods for the energy system are presented in Paper III and for the municipal waste system in Paper IV.

The amounts of N and P in fuels were calculated for the period from 1900 to 2003. The energy content of consumed fuels was obtained from different energy, trade, import and forest statistics (Paper III, Table 1). Fuel properties were adopted from literature sources listed in Table 2 of Paper III. The total amount of N oxides (NO_x) was calculated based on Statistics Finland (2004, years 1980–2003), Savolainen and Tähtinen (1990, years 1950–1979 estimation) and Posch et al. (2004, years 1900–1959).

Historical development of N and P flows in municipal wastewaters was calculated by multiplying the population by the nutrient load per capita. The nutrient load for the period 1952–1967 was estimated to be 4.4 kg N person^{-1} a^{-1} and 0.7 kg P person^{-1} a^{-1} (Vesianalyysitoimikunta 1968). Data on nutrient content of the total municipal wastewaters (E to G) entering treatment plants between 1971 and 1990 were received from Lapinlampi and Raassina (2002). Information on the number of people connected to the wastewater treatment plants was used to distinguish the industrial wastewaters from household wastewaters. Data on the nutrients discharged from municipal wastewater treatment plants to water courses (*T* and *V*) were based on the emission monitoring data (VAHTI database).

The amount and partitioning of N and P in municipal solid waste were determined by multiplying the amount of municipal waste by the percentage of different waste components (organic waste, paper and cardboard, textile and plastic) and by their N and P contents (see Paper IV, Tables 1 and 2).

4. Results

4.1. Situation at the end of the 1990s

The N and P flows in Finland at the end of the 1990s are presented in detail in Paper I, Fig. 4 (Forest industry and use of wood fuels), Paper II, Figs. 2 and 3 (Food production and consumption system), Paper III, pp. 109–112 (Energy system) and Paper IV, Figs. 7 and 8 (Municipal waste system). A summary of the main results is given here.

The N and P flows are divided into three categories:

1) flows between production and consumption sectors;
2) flows to water, air and soil (environmental flows); and
3) recycling and re-use of N and P.

4.1.1. Flows between production and consumption sectors

At the end of the 1990s, agricultural fertilizers [H_{II}] created the largest N and P flows in Finland, 180 000 t N a^{-1} and 29 500 t P a^{-1}, respectively (Table 4). The fertilizers accounted for approximately 65% of N and 60% of P inputs to the soil (Paper II, Figs. 2 and 3). Total average N inputs [C_{II}, F_{II}, H_{II}, V_{II}, X_{II}] to agricultural soil were ca. 53 000 t a^{-1} larger than the outputs from the soil [D_{II}, Y_{II}, AD_{II}], corresponding to an apparent soil surplus of 29 kg N ha^{-1} a^{-1} on agricultural land. P surplus was 23 600 t P a^{-1} (13 kg P ha^{-1} a^{-1}).

The two second largest N and P flows were also in the food production and consumption system: crop yield [D_{II}] 147 000 t N a^{-1} and 21 900 t P a^{-1}, and feed [E_{II}] 116 000 t N a^{-1} and 16 200 t P a^{-1}. Fuel from domestic sources [A_{III}] ranked fourth place with regard to N, with about half of the N in fertilizers. However, if the fuel flows from domestic and foreign sources [A_{III} + B_{III}] were summed, the flow of 167 000 t N a^{-1} would climb to second place on the list. In 2000, 46% of N in fuels originated from peat (domestic) and 34% from coal (imported) (Paper III, Fig. 5). Simultaneously, 47% of fuel P flowed into the energy system in peat, and 42% in wood, including black liquor (Paper III, Fig. 7).

Imported fuel [B_{III}] was the largest of the imported N inputs, 68 000 t N a^{-1}. On the other hand, this flow's importance in the P cycle was low (600 t P a^{-1}). In food and feed [A_{II}], 30 000 t N and 3500 t P were imported annually. The most important imported food and feed groups were oilseeds (32% of imported N and 23% of P) and fodder raw materials (26% of imported N and 24% of imported P). For purposes of comparison, the amounts of nutrients imported in wood were 5000 t N a^{-1} and 600 t P a^{-1}.

Export of food and feed [B_{II}] accounted for 16 000 t N a^{-1} and 2900 t P a^{-1}. The most important exported food and feed products were oats and barley. In forest industry products [M_I + O_I], similar amounts of nutrients were exported (ca. 12 000 t N a^{-1} and 2800 t P a^{-1}). Virtually neither fuel nor waste was exported.

In plant and animal products [G_{II} + I_{II}], ca. 51 000 t N a^{-1} and 9900 t P a^{-1} flowed to the food and fodder processing industry from the agricultural production system. The N flow in plant and animal products was

Table 4: The ten largest N and P flows in the studied four subsystems ((I) Forest industry and use of wood fuels, (II) Food production and consumption, (III) Energy and (IV) Municipal waste) at the end of the 1990s.

	Flow		**t N a^{-1}**	**Flow**		**t P a^{-1}**
1	H_{II}	Fertilizers (agricultural)	180 000	H_{II}	Fertilizers (agricultural)	29 500
2	D_{II}	Crop yield	147 000	D_{II}	Crop yield	21 900
3	E_{II}	Feed	116 000	E_{II}	Feed	16 200
4	A_{III}	Fuel from domestic sources	99 000	F_{II}	Manure	15 900
5	D_{III}	Oxidized N from combustion	75 000	I_I	Use of wood and chemicals (pulp and paper industry)	6300
6	E_{III}	Elementary N from combustion	74 000	F_{III}	Fuel ash	6300
7	Y_{II}	Air emissions from manure and fertilizers, denitrification	72 000	J_{III}	Industrial and imported feed	6200
8	B_{III}	Imported fuel	68 000	A_{III}	Fuel from domestic sources	5700
9	F_{II}	Manure	67 000	I_{II}	Animal products to industrial use	5700
10	N_{II}	Domestic food consumption	33 000	N_{II}	Domestic food consumption	5500

two times larger and the P flow three times larger than the N and P flows in wood to the forest industry [E_I], at 27 000 t N a^{-1} and 3200 t P a^{-1} (Paper I, Table 3). Approximately 39% of N and 40% of P in wood was in the bark. Compared with the amount of N and P in wood, a significant amount of nutrients flowed in the forest industry in various chemicals. Total annual input of N in various chemicals to the forest industry was estimated to be approximately 19 000 t and total input of P 4500 t. Of these, the most important were the urea and the melamine resins used in the wood product industry, which contained about 10 000 t N.

Approximately 33 000 t N and 5500 t P flowed annually to domestic food consumption from the industry, forest foods and recreational fishing, the flow [N_{III}] being the tenth largest of all flows studied (Table 4). For comparison, the N and P intake of domestic animals [E_{II} + J_{II}] was ca. four times larger than that of humans. Annual average N and P consumption per person was ca. 6.5 kg of N and 1.1 kg of P. Around 14% of N and 18% of P in the consumed food (e.g. fish bones, vegetable peelings) ended up in solid waste. When the amounts of nutrients in organic waste are subtracted, the annual average intake of nutrients per person is obtained: 5.5 kg N and 0.9 kg P. The majority of nutrients in consumed food found their way to household wastewaters [R_{II}], containing approximately 26 000 t N and 4100 t P. Municipal organic waste [S_{II}] contained an average of 4800 t N and 950 t P annually.

Regional analysis of wood consumption in the forest industry showed that, overall, 60% of the N and P were consumed within the region from which they originated. South-Eastern Finland (region 5, Figs. 5 and 6 in Paper I) was the major consumer of N and P in wood, in total, per capita and per area. It accounted for 25% of the N and P in consumed stems and imported wood and for 39% of N and P in domestic sawmill chips. If the neighbouring regions 3 and 6 are added, 65% of N and 71% of P input is covered, respectively, in an area that represents only 32% of Finland's total land area.

4.1.2. Flows to water, air and soil (environmental flows)

The flow of oxidized N from the combustion processes to air [D_{III}] was the largest of the environmental N flows (75 000 t N a^{-1}) (Table 5). Oil consumption by traffic produced the highest (61%) N emissions (NO_x and N_2O), followed by the combustion of coal (10%) and combined wood and black liquor (10%). NO_x emissions per unit of energy produced were highest from traffic and lowest from combustion of black liquors and natural gas.

A flow almost as large (72 000 t N a^{-1}) was created in air emissions from agriculture (manure and fertilizers, including denitrification into N_2) [Y_{II}]. N leaching from agricultural land to water (AD_{III}, 33 000 t N a^{-1}) was the third largest. Denitrification accounted for 35 000 t N a^{-1}, being close to the value for leaching. The relevance of denitrification for atmospheric flows is low, as it only increases the amount of N_2 in the atmosphere, but high for the agricultural soil nutrient balance since soil N is lost.

At the end of the 1990s, almost 700 000 t of waste from pulp and paper mills were annually transported to landfills. Due to low data availability, it was very difficult to estimate the amount of nutrients in the waste, and thus, large ranges of 2000–8000 t N and 1400–4900 t P were derived. Based on the mass balance calculation and the tendency of N to escape to the air in combustion processes, the amount of N in the wastes is likely to be at the low end of the range, but the amount of P at the high end. In Table 5, the average figure of 3500 t P a^{-1} is presented, with this being the largest environmental P flow. The most important waste fractions with regard to nutrients were wastewater treatment sludges, fibre and coating colour sludges and ashes from energy generation. The two second largest environmental P flows were leaching from agricultural land [AD_{II}] and fuel ash to landfills [H_{III}], both accounting for 2400 t P a^{-1}.

In municipal solid waste, some 7000 t N a^{-1} and 800 t P a^{-1} were deposited to landfills. Organic waste accounted for ca. 55% of the total annual municipal solid waste N flows and 75% of the annual municipal solid waste P flows.

Municipal wastewater treatment plants discharged 5900 t N a^{-1} and 100 t P a^{-1} to marine waters and 7600 t N a^{-1} and 150 t P a^{-1} to freshwaters, resulting in the fourth largest N flow to the environment (Table 5). The purification efficiency of P was over 90%, but only ca. 44% for N. Due to the high P purification efficiency of municipal wastewaters, municipal wastewater discharges [T_{IV}, V_{IV}] were not high on the environmental P flow list.

P emissions associated with rural household wastewaters [S_{IV} + U_{IV}] were ca. 150 t higher than the P emissions from wastewater treatment plants. N discharges associated with rural household wastewaters were ca. 2800 t N a^{-1}. They were about the same size as the forest industrial wastewaters

Table 5: Five largest environmental N and P flows in the four subsystems ((I) Forest industry and use of wood fuels, (II) Food production and consumption, (III) Energy and (IV) Municipal waste) at the end of the 1990s.

	Flow		t N a^{-1}	Flow		t P a^{-1}
1	D_{III}	Oxidized N to air from combustion	75 000	T_{I}	Landfill deposition of forest industries waste	3500
2	Y_{II}	Air emissions from manure and fertilizers, denitrification	72 000	AD_{II}	Leaching from agricultural land	2400
3	AD_{II}	Leaching from agricultural land	33 000	H_{III}	Fuel ash to landfills[a]	2400
4	T_{IV}, V_{IV}	Municipal wastewater discharges to water	14 000	M_{IV}	Landfill deposition of municipal sewage sludge	900
5	L_{IV}	Landfill deposition of municipal solid waste	7000	L_{IV}	Landfill deposition of municipal solid waste	800

[a] Partly overlapping (wood fuels) with flow T_{I}.

(originating almost 100% from the pulp and paper industry), which accounted for 2900 t N^{-1} and 300 t P a^{-1}. Many large forest industry plants are located by the sea and, as a consequence, in Finland, a large proportion of direct nutrient emissions, 34% of N and 40% of P emissions, ended up in the sea (Paper I, Figs. 7 and 8). By being the main user of N and P in wood, the South-Eastern Finnish pulp and paper industry (Region 5) was also the main discharger of N and P in wastewaters.

4.1.3. Recycling and re-use of N and P

Almost half of the N and about 30% of the P flowing into the forest industries is re-used by energy production, mainly in black liquor and bark. In the combustion process, N is either oxidized to NO_x or N_2O or transformed to elementary N_2. It is then emitted to the atmosphere, but a part of it may be returned to forest soil in atmospheric deposition. P in the combustion process stays in the ashes and is mainly deposited to landfills. Annually, only a quantity representing some 3% of total P content in ashes from energy production in the forest industry is spread to forest soil as fertilizer. The re-use rate of paper in Finland is 70%, and approximately 300 t N and 200 t P were estimated to return to the forest industry from domestic consumption. This accounts for 0.5% of the forest industries N intake and 3% of the P intake.

In the food production and consumption system, several possibilities to recycle or re-use exist. Manure from animal production was mainly used as a fertilizer in plant production, but some 30% of the N in the manure is lost to air as NH_3. In plant and animal products [G_{II+} I_{II}], ca. 51 000 t N a^{-1} and 9900 t P a^{-1} flowed to the food and fodder processing industry from the agricultural production system. An estimated 30% of these flowed back to the agricultural production system in plant-derived by-products used as fodder and animal-derived by-products used as feed for fur animals.

Sewage sludge was estimated to contain 3200 t N a^{-1} and 3500 t P a^{-1}. Of this, approximately 25% was returned to agricultural production after treatment by anaerobical digestion, lime stabilization or composting.

4.2. Historical changes in N and P flows

4.2.1. Energy system

During the 20th century N in fuel grew almost 20-fold, from 8700 t to 140 000 t per year, and P in fuel grew 8-fold, from 800 t to 6000 tonnes per year (Paper III). NO_x emissions from the energy system increased, reaching a maximum (87 000 t N) in 1981, and then declining by 28% until the end of the century (Paper III). More than half of the NO_x since 1980 has been generated by traffic.

4.2.2. Waste and wastewater management system

The annual flow of N and P in untreated municipal wastewaters first increased more than 6-fold between 1952 and 1990 but then decreased between 1990 and 1994, N by approximately 5% and P by approximately

20% (Paper IV). In 1995–1999, the total amount of nutrients in municipal wastewater was again slightly larger than in 1994. Between 1971 and 1997 (an average of 1995–1999) the efficiency of nutrient removal improved steadily. At the end of 1990s P removal efficiency exceeded 90%, and the efficiency of N removal was 36%. The amount of nutrients in rural household wastewaters decreased throughout the study period, reflecting changes in the sewage industry and in the degree of urbanization.

The amount of sewage sludge produced doubled between 1975 and 1997, from 72 000 t in 1975 to 153 000 t a^{-1} in 1997, the average in 1995–1999 being 145 000 t a^{-1}.

The flows of N and P associated with municipal solid waste grew until 1990. N reached a maximum at 12 000 t and P at 1700 t (Paper IV). Growth in the generation of municipal solid waste was particularly fast during the 1980s, when the amounts of both N and P in municipal solid waste doubled.

5. Discussion

5.1. Magnitude of the Finnish N and P flows

Of the four subsystems studied, the food production and consumption system (Paper II) and the energy system (Paper III) created the largest N flows in Finland. For the creation of P flows, the food production and consumption system (Paper II) was clearly the largest, followed by the forest industry and use of wood fuels (Paper I) and the energy system (Paper III). These results are similar to those of other SFA studies on N and P elsewhere in the world (van der Voet et al. 1996, Zheng et al. 2000, van Egmond et al. 2002, Galloway and Cowling 2002, Howarth et al. 2002, Smil 2002). However, some regional differences exist. In the agriculture-intensive Netherlands, the input of N in fertilizers to crop and grass production was about 10-fold that to combustion processes in fuels (van der Voet et al. 1996). By comparing NO_x emissions with the use of N fertilizers in the USA Howarth et al. (2002) found the significance of the energy system for N flow to be significantly higher than the world average. Globally, the release of N to the environment from fuel combustion as NO_x accounted for about one-quarter of the amount of N in fertilizer consumption, while in the USA, the corresponding figure was almost two-thirds. In Finland, the significance of the energy system in the N flows was higher than the global average but lower than in USA, as the Finnish emissions of NO_x included about 40% of the N input in fertilizers.

Eutrophication is the most urgent water protection problem in Finnish fresh waters and the Baltic Sea. This study gives a general view of Finnish N and P flows, revealing the main contributors to the eutrophication problem. However, smaller, regionally or locally important flows are masked as a SFA performed on a national level highlights large flows. Examples of locally important nutrient flows include nutrient loads from fish farming and fur farming, which can significantly deteriorate surface and groundwaters, although their contribution to total N and P loads in Finland is minor (fish farming 1% of N load and 2% of P load; fur farming 1% and 0.4%, respectively) (Nyroos et al. 2006).

The creation of N flows varies significantly regionally also on a large scale (Galloway and Cowling 2002). Asia is the leading region, with a creation of 68.9 Tg N a^{-1}, followed by North America (28.4 Tg N a^{-1}) and Europe (including the former Soviet Union, FSU) (26.5 Tg N a^{-1}). When compared on a per capita basis, N creation in North America is four times larger than the world average (100 kg N $person^{-1}$ a^{-1} versus 24 kg N $person^{-1}$ a^{-1}). North America is followed by Oceania (63 kg N $person^{-1}$ a^{-1}) and Europe (including FSU) (44 kg N $person^{-1}$ a^{-1}). Based on this study, the Finnish per capita creation of N (96 kg N $person^{-1}$ a^{-1}) is very close to that of North America and more than double the average European creation. The Finnish per capita creation of P is approximately 12 kg P $person^{-1}$ a^{-1}, food production accounting for 85%. The Finnish figure is more than double the global creation of P (around 5 kg P $person^{-1}$ a^{-1}; calculated on the basis of figures presented by Smil 2000). Per capita intake of N in Finland is on the same level as in the United States and is about two times larger than in Bangladesh (Paper II). The Finnish NO_X emissions per person are about three times higher than the global average (Paper III). Although the figures are not completely comparable due to variability in databases and calculation methods in different studies, they do show that the Finnish per capita contribution to the global enlargement of the nutrient flows is significant. Reasons for this are relatively high energy and meat consumptions.

Finnish energy consumption per capita is almost two times higher than the European average, and only some 20% smaller than the energy consumption in energy-intensive countries such as Canada and the

United States (Statistics Finland 2004, 2005a). The Finns use more than four times the energy per capita than the average person globally (Statistics Finland 2005a). The share of N-rich coal and peat is high in Finnish energy production, which also increases the relative N creation. Compared globally, Finnish meat consumption is on the same level as in Sweden, Norway, Poland and Chile (FAO 2007). In countries such as the United States and Australia, the meat consumption per capita is nearly two times higher than in Finland. On the other hand, in most developing countries, meat consumption is approximately one-tenth of the Finnish consumption. Meat is rich in N, and thus, large intakes increase N flows.

5.2. Closing the N and P cycles

One of the basic aims of the IE approach is to find possibilities for closing the material cycles (see Section 1.2.1). This study revealed that the Finnish N and P cycles are not ideal in this respect because the conditions of level III ecology are not fulfilled. Instead, all four nutrient subsystems evaluated can be considered linear or only partly cyclical (representing type I or type II ecology).

Vast amounts of N and P enter the forest industry from the Finnish forest ecosystem, other industry sectors and abroad (Paper I). From the production system, nutrients flow in products to domestic consumption or exports or as environmental emissions to water, air or landfill storages. Only a small amount of P is intentionally returned to the forest ecosystem in ash-based fertilizers. In addition, some of N does return unintentionally to forest ecosystems from combustion through atmospheric deposition.

In the food and fodder production system (Paper II), there are several linear nutrient lines. First, both N and P inputs to soil are larger than the outputs. Long-term soil nutrient surplus increases nutrient leaching from soil to waters and increases the risk of groundwater N contamination. Here, denitrification and artificial denitrification can serve as problem-solving methods (see e.g. Schnobrich et al. 2007). Second, N consumed by farm animals is not totally transferred to the animal products or back to the agricultural soil in manure, but a large fraction (25% of the N consumed by animals in their food) is lost to the atmosphere as ammonium. Furthermore, nutrients consumed in foods by humans are mainly extracted, and depending on the efficiency of the wastewater management, either lost to waters or air or captured to sludge (Paper IV). P losses from the municipal waste system decreased throughout the study period, as techniques for P removal from wastewaters improved. Losses of N to water and air remained relatively high, and little N was returned back to the agricultural production system in sludge. Between 1995 and 1999 ca. 50% of P and 10% of N in municipal waste were recycled.

Linearity in nutrient flows is also seen in the energy system, in which N and P stored in long-term geological stocks (coal, peat) are released in combustion of fossil fuels and related oxidation of atmospheric N (Paper III). Long-term geological P stock is also converted to a reactive form in P fertilizer production (Paper II).

All of the four systems cause N losses to air. N lost to air as NO_x or N_2O is difficult to recapture or control. All the lost N can be considered a problem in the sense that it is lost from the system and its recapture requires energy.

Nutrient recycling can only be achieved through integrated activities in all relevant fields. Many possibilities for closing the nutrient cycles can be found, and some examples are presented below. For example, waste can be a valuable resource instead of a problem. In the use of wood and wood fuels, one recommendation is to return nutrient-rich wastes, especially ash from combustion, back to forests as fertilizers (Paper I, Paper III). In municipal waste, recovery of nutrients from the system can be improved by increasing the nutrient recycling in sewage sludge utilization (Paper IV). At the end of the 1990s in Finland, sewage sludge contained about 2.4% of the N and 11.8% of the P applied to agricultural soils as synthetic fertilizers (Paper II, Paper IV). Even if it were technically and economically possible to return all nutrients in municipal wastewater, sludge and organic solid waste to the agricultural soil, these would only replace ca. 17% of the nutrients in inorganic fertilizers (Paper II).

The amount of ammonium lost from manure to the atmosphere depends on the properties and the treatment and storage methods of the manure, on weather conditions and on soil properties, among others (Grönroos et al. 1998). In the spreading phase, the ammonium emissions from slurry can be significantly reduced with such methods as injection and incorporation by harrowing compared with the traditional broadcast spreading (Mattila 2006). Use of advanced technologies and coverage of the manure storages are cost-efficient ways to reduce ammonium emissions (Grönroos et al. 1998), thereby increasing the possibilities of N cycling.

Agricultural waste, such as manure, straw and litter, as well as sludge or biowaste from municipalities can be utilized in production of biogas either on a farm level or on larger facilities. Biogas is a good energy source for heat and power production or for traffic biofuel. In addition, nutrient-rich residue suitable for fertilization is produced in biogas production. Biogas can replace fossil fuels and reduce greenhouse gas emissions, reduce waste problems in agriculture and municipalities and reduce the need for inorganic fertilizers.

In the current open economies, completely closed cycles are in practice impossible on a national scale, let alone on regional or sectoral scales. Raw materials and resources are needed from abroad and other regions and sectors, which inevitability leads to the openness of the N and P flows as the nutrients are moved in the products (see also discussion on system boundaries in Section 5.4). Moreover, sustainable nutrient management is not the only target, and other environmental aims, agricultural and energy policy, employment policy and market situations drive the nutrient flows directly and indirectly. However, as the biogas example above shows, there are win-win solutions in which many aims can be fulfilled.

An important question related to the closing of the cycles is whether the quality of substance can be maintained in recycling or reuse in such a way that it can be utilized. For example, in the case of N and P quality problems have emerged in both ash and sludge recovered and recycled for fertilizer due to harmful substances. Moreover, when defining whether a certain system is closed or not, taking into account the spatial dimension of the flows and stocks is important. For example, in Finland, most of the crop production area is located in southern and western parts of the country, whereas farming animals tend to more frequently be situated in eastern and northern Finland. This complicates closing the cycles of feed and manure, and may in fact cause dislocation of nutrients instead of their recycling. An interesting are of research would be the analysis of the spatial dimension of nutrient flows.

Reduction of environmental impacts such as eutrophication and climate change, is the main aim of the environmental policy. Closing the cycles can facilitate this. However, when striving to close cycles, it is important to weight both benefits and disadvantages. Complete closure of cycles may, for instance, mean more transportation and consequently more use of fuels and greater emissions. Therefore, closing the cycles cannot be the primary aim of environmental policy. A holistic approach is needed to find a balance between different solutions.

5.3. Possibilities for diminishing N and P flows

Dematerialization in N and P flows, here meaning reduction of the inputs of N and P to the human economy, would reduce the amount of nutrients cycling in the systems. In many cases, the outputs of nutrients to water, air and soil would also decrease. Concomitantly, the energy consumption of the system would decrease, as less energy is needed in, for example, the fertilizer and other chemical industries and in the transportation sector. As presented in Section 1.2.2, alternative ways to promote dematerialization include increasing efficiency, substitution, re-use or recycling and sharing. Sharing, however, is obviously not a relevant option in nutrient management. The potential for re-use and recycling in the systems studied was discussed in the previous section, as the concepts of closing the loops and dematerialization by re-use or recycling are practically the same.

Historical development of the nutrient flows was investigated in two subsystems. In the flows of fuel N and P, a strong increasing trend was seen. The amounts of fuel and emission N were about the same size and grew similarly until the 1980s. After this, the amount of fuel N continued to grow, while N emissions started to decline slowly due to increases in energy efficiency, technological improvements in combustion processes and changes in the structure of power production, including the introduction of nuclear power to the Finnish energy system. In the municipal waste system, total flows of N and P increased from 1952 to 1990, but then levelled off or decreased, and the efficiency of nutrient, especially P, removal from the municipal waste waters improved steadily.

In the subsystem of the forest industry and use of wood fuels, nutrient inflows could be by debarking forest trees and leaving the nutrient-rich bark in the forests. However, bark is currently a significant energy source, and if left in the forest, it must be replaced with other fuels, most likely fossil fuels. This shifts the negative environmental impact to other problems, such as depletion of renewable natural resources and global warming. Reduction in the chemical inputs to industrial processes is another option for N and P dematerialization in the forest sector that requires more study, as an increase in the chemical consumption can lead to an increase in nutrient emissions to waters (Paper I). Easily soluble nutrients ending up in wastewater treatment can disturb the sensitive biological treatment system and seriously reduce the efficiency of purification. Nutrients are also added to the wastewater treatment plants to improve microbiological purification processes. Excess soluble nutrients pass through the treatment system, ending up in water bodies, and thus, causing eutrophication problems.

More balanced and efficient use of nutrients, which can be achieved either by monetary incentives or by developing quality control and quality assurance of the production systems, and education of farmers, are potential means of reducing inputs and losses of N and P in the agricultural production system (Paper II). Higher efficiency here means that the same total yield can be produced with a smaller area and with less nutrient inputs, which leads to a reduction in nutrient losses from the agricultural production system. In addition, more efficient nutrient cycling on farms could be supported by developing monetary incentives in accordance with the existing agro-environmental support schemes (compliant with EU Regulation EC/1782/2003).

Organic farming has been proposed as one solution for reducing the nutrient losses from the agricultural production system. However, as discussed in Paper II, crop yields in organic farming are usually lower than in conventional farming. This means that more agricultural production area would be required to produce the same total amount of food and feed, which in turn can result in nutrient losses similar to the current level, even though the losses per hectare are lower in organic farming. Granstedt et al. (2005) reported that N surplus is, on average, approximately 30% lower on farms integrating crop and animal production, recycling nutrients and utilizing biological N fixation than on conventional farms. However, the required agricultural area of recycling farms to produce a food basket is 25% larger than in conventional agriculture.

Although reduction of the current excess intake of the Finnish population of N and P to recommended nutrient intake would in practice be difficult, in the long term this is an important task. Increasing the intake of plant products and reducing the intake of animal products would decrease the nutrient outputs in two ways. First, when less nutrients are consumed by humans, less are also excreted to wastewaters and solid waste, and outputs to water and soil decline. Second, reduction in meat consumption would also decrease nutrient losses to waters and air from the agricultural production system. Less animals and a smaller agricultural production area would be needed to meet the consumption demands, as approximately 7 kg of feed N are needed to produce 1 kg of edible N in animal products (Smil 2002). In Finland, about 70% of N and P in the harvest are directly fed to animals (Paper II).

The N content of fuels is one of the most important factors in the generation of NO_x emissions. Use of fuels containing less N helps to reduce these emissions and the N and P flows in the energy system overall. For example, the reduction of N-containing chemicals in pulp production can also reduce NO_x emissions to air (by decreasing the N content of black liquor) (Telkkinen 1997). Other important ways to reduce NO_x emissions to air include technical methods, such as vehicular catalytic converters and de-NO_X installations, and changes in power production and consumption structure. Concerted efforts should directed towards curtailing the growing volume of energy consumption. Besides lowering NO_x emissions, this also reduces other atmospheric emissions, such as greenhouse gases, and results in a reduction of the use of resources. The growing of greenhouse gas emissions and the consequent climate change are doubtless the most urgent challenges of the environmental policy, necessitating that all abatement measures be taken into use.

The emissions to the environment are often more important for environmental changes than the intake of a certain material or substance. If a substance accumulates in a permanent or long-term stock, this can prevent its harmful emissions to the environment. Consequently, it is important to understand the potential accumulation of a substance in stocks and any transformation processes. This substance stock analysis is especially relevant for substances with low or zero degradation rates, where accumulation is of importance, for substances with low mobility and for substances with low or no secondary biomagnification (Karlsson et al. 2004). According to this study, high concentrations of N and P are present in products flowing relatively quickly through a society. A long-term societal stock of nutrients in wood in constructions was estimated to contain 82 000 tonnes of N and 2700 tonnes of P (Paper I). In future, this stock potentially forms a flow to either the energy system, as the wooden construction waste is often utilized as a energy source, or the waste system. In the former system, the construction waste would probably not add any emissions, since the new energy source would most likely replace other energy sources, such as coal. In the latter system, however, deposition to landfills would create another stock, from which the nutrients would slowly be released after decomposition.

5.4. Importance of system boundaries

An interesting question is how the results and their interpretation would change if the system boundaries were different. This study considered four N and P subsystems in Finland, the borders of the country serving as the system boundaries. The results would have been different had the study included only one municipality in Finland or, on the other hand, a larger area, such as Europe or the whole world. Generally, the smaller the system, the more outside influence there likely is. The Finnish nutrient cycles are largely influenced by imports and exports; for example, imported fuels bring vast quantities of nutrients to the country and cause significant N emissions to air. Finnish consumption, in turn, has an influence on the nutrient flows abroad. As an example, production of imported food and feed causes nutrient leaching to waters and emissions to air in the place of production. Thus, the overall size of the Finnish N and P cycles is actually larger than implied by our results. Moreover, the environmental impacts of the nutrient emissions (wastewater, atmospheric emissions through deposition) from Finland are far-reaching in the Baltic Sea region. According to Sterr and Ott (2004), larger areas may be more suitable for closing material loops and creating sustainable industrial ecosystems, as there are more actors carrying out a specific function and thus contributing considerably to system stabilization. However, elucidation of the correct size and the optimal system boundaries in industrial ecosystem requires further investigation.

In this study, four Finnish N and P subsystems were investigated in detail. Although all of these subsystems are ubiquitous and essential for these nutrient flows, a complete picture of the Finnish N and P systems could not be drawn. For example, the internal cycle of the forest system or the water system was not analysed. Many other industries and their emissions and wastes were also not studied. Examples include construction industries and other chemical industries besides the fertilizer industry. Moreover, some secondary effects, such as P release from sediments due to anoxia caused by eutrophying emission or nutrient leaching caused by construction of reservoirs to meet the needs of the energy sector, were not analysed. The systems studied cover most of the N and P emissions to the environment and also their internal flows in the societal system, as the construction industries, for instance, are partially analysed in connection with the use of wood (wood products and N and P stock in constructions). However, adding information on natural systems of N and P would increase the holistic understanding of N and P systems in Finland and the interaction between natural and societal stocks and flows of N and P.

In this study, all Finnish atmospheric NO_x emissions were considered to arise from the energy sector. However, by using a different system definition, NO_x emissions could be allocated to other sectors, such as agriculture, according to the use of energy and machinery.

As no predictive modelling was done, the approach presented here gives a static picture of the past and present N and P flows in Finland and is unable to reveal any future changes. Predictive modelling, especially dynamic modelling, requires abundant initial data, and the complicated interactions between flows are often troublesome to simulate. To model future Finnish N and P flows, more research is needed on different scenarios of the drivers affecting the flows.

It should also be noted that this study dealt with the flows of total N and P. The impact of such emissions as NO_x, N_2O and NH_3 will depend on the actual chemical compositions of the substances and on the receiving environments. These aspects were not considered in detail here. An input-output method is commonly applied in MFA studies to evaluate the material flows of a country (Eurostat 2001). A new extension of the model is to connect the environmental emission factors to the material flows and then use the LCA methodology to calculate the environmental impact of the material flows (Engström 2006). The same approach could also be applied in SFA studies to assess the actual environmental impact of different substance flows.

5.5. Uncertainties

Several factors, including variation in nutrient concentrations and dry weights, applied bark percentages, basic densities and possible inaccuracies of statistics, affect the present results. Generally speaking, the reliability of the statistics in Finland is high. Estimates on, for instance, fertilization, wood felling and consumption, harvest, animal production, energy production and consumption, imports and exports and human consumption are based on official statistics. Uncertainties in these N and P flows can be assumed to be relatively low. Also wastewater emissions from municipal and industrial wastewater treatment plants originate from monitoring data with high accuracy. Uncertainties are relatively high in many environmental flows, such as agricultural air emissions. Relatively large uncertainty relates also to approximation of the total leaching from agricultural soils because leaching varies considerably depending on soil type, slope and cultivation methods. The long statistical series used to evaluate the subsystems of energy and municipal waste systems were not wholly uniform, and the older the data, the more uncertainties exist. When the data source changes, some inconsistencies arise (for example in the time series for wood fuels). An unrealistic abrupt increase occurred in the NO_x estimate in 1980 (Paper III, Fig. 8). Relatively accurate estimations on municipal solid waste generation and composition can only be found from the 1990s onwards. The uncertainties were minimized by using an extensive range of reference sources and making comparisons between these sources.

One source of uncertainty is caused by the annual variation in flows. For example, crop yield and its N and P content is largely affected by the weather of the growing season. For this reason, annual averages over the period 1995–1999 were used to reduce the effect of extreme results when drawing a picture of N and P flows at the end of the 1990s. Because of data restrictions, a detailed picture of the energy system flows was achieved for one year only (2000). In Finland, the year 2000 was warm, which reduced the need for district heating, and consequently, decreased the use of peat and other heating fuels. Consumption of light fuel oils and motor oils was lower than in earlier years because of the rise in oil prices. The availability of hydropower was good, and a relatively large amount of electricity was imported (Ministry of Trade and Industry in Finland 2001). These coinciding factors decreased the nutrient flows, especially for peat, compared with the average over the last several years.

A more accurate analysis of industrial and waste flows would have been achieved with more detailed mill-specific process information instead of a desktop investigation. This is especially true for the forest industry, but also for the food and fodder processing industry. For example, the composition of wastes varies from plant to plant and also seasonally within one plant. Due to the lack of specific information, generalizations had to be made about the use of chemicals in processes and nutrient concentrations of different waste fractions.

Quantification of N flows tends to be more uncertain than quantification of P flows. Nitrogen's tendency to escape to air from combustion processes, fertilization, tillage, manure management and wastewater treatment complicates estimations. N fixation in different parts of the system that were not considered may have caused miscalculations. For example, in wastewater treatment, N fixation can be a significant source of N (Slade et al. 1999).

Uncertainties can be estimated qualitatively (as above, or by assessing the data quality as in Paper I, Appendix I) or quantitatively. A method developed by Hedbrandt and Sörme (2001) is designed to be used in SFA, in which the uncertainties usually cannot be analysed by traditional statistical methods. The method was tested in the subsystem of food production and consumption (Paper II) and found to be suitable for this type of study. The uncertainty analysis showed that the final result may contradict to the primary results. In the subsystem of food production and consumption, the primary (or likely) values gave an indication of soil surpluses of 29 kg N ha^{-1} a^{-1} and 13 kg P ha^{-1} a^{-1}. However, taking into account the uncertainties associated with the calculations, there may even be a loss of N from the Finnish agricultural soil. The large range is explained by the uncertainty in estimation of N_2O and denitrification losses to air. Thus, a quantitative uncertainty assessment is recommended for use in SFA to support the interpretation of the results.

5.6. SFA as a decision-making tool

The aim of SFA is to produce information about different environmental problems, their origins and potential future developments for policy makers. More specifically, SFA identifies problematic flows of a given substance and the origins of the flows. Changes in flows and stocks over time, past and future, can also be monitored. Moreover, SFA can be used to predict the effectiveness of pollution abatement measures on environmental problems. Various future scenarios, political decisions and other methods can be used to forecast probable changes in consequent flows and environmental pressures. This study provides an example of an application of SFA study in Finland. Only a few previous SFA studies on Finnish societal systems exist (Granstedt 2000, Korhonen et al. 2001). Nutrient stocks, flows and transformations in natural systems have been widely investigated (some examples from forests include Finér 1989, Aarnio et al. 1995, Kauppi et al. 1995, Piirainen 2002, Palviainen 2005, from agriculture Kaila 1948, Hartikainen 1979, Mäntylahti 2002, Saarela 2002, Salo & Turtola 2006, Syväsalo et al. 2006, Mattila 2006, and from waters and water emissions Kauppi 1984, Rekolainen 1993, Pitkänen 1994, Kortelainen and Saukkonen 1998, Vuorenmaa et al. 2002, Lehtoranta 2003, Kortelainen et al. 2006, Lepistö et al. 2006, Vahtera et al. 2007). Atmospheric and water emissions are also regularly monitored and reported by industries and administration. This study yields information on N and P flows and the relative significance of different flows in Finnish society. Origins of different N and P emissions can be traced back on the basis of the data provided here. For instance, in the forest industries' water emissions, chemicals seem to play an important role. In addition, no estimates of the N and P content have been tendered for many of flows analysed here, solid municipal waste being a good example. This knowledge of nutrient potential is relevant when, e.g., designing new ways to utilize sludge and composted biomass. Furthermore, the study illustrates and discusses how the concepts of IE, industrial metabolism, closing of material cycles and dematerialization can be approached in practice.

Although SFA studies may produce useful information about various environmental problems, the method is rather simplistic and has several limitations. In a synopsis on SFA and LCA by Antikainen et al. (2005), several pitfalls of SFA were identified. These problems can, however, be overcome by, e.g., supporting the analysis with other methods (Table 6).

When investigating different substances using SFA, the focus of the study varies depending on the properties of the substance in question. For example, the biological and geochemical transformation processes differ, and the relevant transport media are also variable. For example, in organic materials, such as food and wood, N and P are always connected, and exploration of metal and electronic products is less important. N and P also flow rather quickly through a society, whereas many metals form long-term stocks. Due to the connection, it is advantageous to explore N and P in parallel. N and P also differ relative to each other. In cycling of N, atmospheric cycle and microbial processes especially in soil are important, with N easily "escaping" from a solid media to the

Table 6. Challenges of SFA studies and suggestions for improvement.

Challenge	**Suggestions for improvement**
SFA by definition deals with a single substance. If measures are taken to reduce the use of this substance by replacing it with another substance, problems connected with the new substance are not revealed (Udo de Haes et al. 1997).	Parallel SFAs can be conducted in order to analyse the connections between substances. Supplementary SFAs need not to be as extensive as in the main study. A qualitative analysis of side-effects could also be done.
SFA considers only the total mass of the studied substance flowing in the system, but certain forms of a substance can be very harmful, while others are relatively inert.	Add information on the form of the studied substance. By doing this, it is also possible to apply LCA methodology to calculate the environmental impact of the substance flows.
SFA does not study energy flows, total material intensity of a system, monetary flows or the wider cultural or social contexts.	Other sustainability aspects can be analysed by using another supporting method. A literature-based qualitative analysis can also illustrate the main points of other sustainability aspects.
Interdisciplinary know-how and understanding are needed to construct even relatively simple models to represent the complicated flows and environmental impacts in the real world accurately.	A common problem in environmental sciences. Members of different scientific fields, preferably from both natural and social sciences, should be included in the study group.
SFA requires a substantial amount of data. Modelling is work-intensive, especially where the dynamics of flows and their potential future trends are concerned.	As above, a common problem in all sciences. An interdisciplinary study group and stakeholders supporting the study may facilitate data collection.
SFA studies are usually presented without uncertainty intervals, giving a false impression of accuracy.	Use of uncertainty or sensitivity analysis improves the quality of data analysis.

atmosphere. These escapes are difficult to quantify accurately, and this property of N increases the uncertainty of SFAs. P does not have a significant atmospheric cycle, and thus its flows are easier to trace and quantify.

A single SFA is usually not sufficient to make any specific recommendations. Neither can SFA studies be seen as a direct basis for decision-making, even at the micro level, where municipalities are concerned (Lindqvist 2002). Van der Voet et al. (1999) suggest using SFA indicators to support environmental policy. To be useful in decision-making, points for comparison, such as development trends or reference values, are needed. However, trends and reference values may be difficult to obtain.

When considering the applicability of SFA studies, it is important to bear in mind that similar challenges are related also to other methods such as MFA, LCA and MIPS. They are all data-demanding and work-intensive, require interdisciplinary know-how and understanding and often need to be supplemented with uncertainty or sensitivity analysis. They also usually measure only one facet of sustainability, and in order to draw a complete picture, supporting methods are needed. Differences and similarities of SFA, MFA and LCA were summarized by Kytzia and Nathani (2004). The objectives of the study determinate which method(s) is the most applicable.

6. Conclusions

The flows and stocks of N and P in Finland were studied in four subsystems using SFA as a research method. The main contributors to the N and P flows were agriculture and the energy system. These also produced the largest N and P flows to the atmosphere and waters. This national-scale study gives us a general overview of Finnish N and P flows, but smaller, regionally or locally important flows are not revealed. Examples of local key nutrient flows include the nutrient loads from fish farming and fur farming, which can significantly deteriorate surface and groundwaters, although their contributions to the total N and P loads in Finland are small. The contribution of Finland to global N and P flows is low, but when compared on a per capita basis, the Finns are one of the largest producers of these flows.

The analysis revealed the openness of all four systems studied. The openness is due to the high degree of internationality of the Finnish markets, the large-scale use of synthetic fertilizers and energy resources and the low recycling rate of many waste fractions. Reduction in the use of fuels and synthetic fertilizers, reorganization of the structure of energy production, reduced human intake of nutrients and developments in technology are crucial for diminishing N and P flows. To enhance nutrient recycling and replace inorganic fertilizers, recycling of wastes, such as wood ash and sludge, could be promoted.

SFA usually does not provide a sufficiently detailed basis for decision-making, but it does give useful information about the relative magnitude of flows and can reveal unexpected losses. SFA studies can be supported by other methods such as LCA. Because uncertainties are high in this type of analysis, the use of quantitative uncertainty analysis is recommended. Sustainable development is a widely accepted target for all human action. SFA is one method that can help to analyse whether the goal of a more sustainable society is being met. SFA's strength is that by using it a holistic picture of different natural and societal systems can be drawn. When the environmental impact of a certain flow is known, the method can also be used for prioritizing environmental policy efforts.

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